

H33

REVIEW OF MARSHALL  
ISLANDS FALLOUT  
STUDIES

Presented by  
Edward T. Lessard  
Brookhaven National Laboratory

9/30/86

Rongelap File 5

HARRY BROWN'S Files, NV

## Summary

Persons who were present on March 1, 1954, at Rongelap Island, Rongelap Atoll, Sifo Island, Ailingnae Atoll, and Utirik Island, Utirik Atoll in the Marshall Islands have been examined by medical specialists to determine if any observable effects occurred as a result of exposure to radioactive fallout from the Pacific weapon test known as Operation Castle BRAVO. Medical specialists have reported short-term effects exhibited over a period of many months and possible long-term effects exhibited over many years. A study was undertaken to reexamine thyroid-absorbed dose estimates for people who were exposed accidentally at Rongelap, Sifo, and Utirik Islands. The study included: 1) reevaluation of radiochemical analysis to relate results from pooled urine to intake, retention, and excretion functions, 2) analysis of neutron irradiation studies of archival soil samples to estimate areal activities of the iodine isotopes, 3) analysis of source term, weather data, and meteorology functions predicting atmospheric diffusion and fallout deposition to estimate airborne concentrations of the iodine isotopes, and 4) reevaluation of radioactive fallout contaminating a Japanese fishing vessel in the vicinity of Rongelap Island on March 1, 1954, to determine fallout components. The relative location of the exposed people is given as Figure 1.

The original estimates of external whole-body dose from the acute exposure were 1.75 gray (175 rad) at Rongelap and 0.14 gray (14 rad) at Utirik (Cr56). The first estimate of thyroid dose from internal emitters in Rongelap people was 100 to 150 rep (Cr56). Thus the first estimate of total thyroid absorbed dose was 2.68 to 3.15 gray (268 to 315 rad) for Rongelap people in general and for internal plus external exposure.

In 1964, three teenage girls who were exposed in 1954 underwent surgery for benign thyroid nodules. In 1964, 3 to 4-year-old child thyroid dose was reexamined by James on the basis of 1) urine bioassay results and 2) a range of values for thyroid burden of  $^{131}\text{I}$ , thyroid mass, and uptake retention functions for iodine (Ja64). In addition two modes of intake were considered, inhalation and ingestion. For 3 to 4-year-old girls the extreme range of thyroid dose from internal emitters was estimated at 2 to 33 gray (200-3300 rad). The most probable total thyroid dose was in the range of 7 to 14 gray (700-1400 rad). The James estimate of most probable total thyroid absorbed dose to the child was 2 to 5 times higher than the estimate reported by Cronkite for Rongelap people.

The value for the James estimate of total thyroid dose was extrapolated to other ages and to the Utirik people and reported along with medical effects by Conard (Co74). The number of radiation-induced thyroid lesions per million person-rad-years at risk was tabulated by Conard for the Rongelap and Utirik exposed populations. It was clear that the risks of radiation induced benign and cancerous lesions were not comparable between the two atolls for any age grouping. The thyroid cancer risk for the Japanese population exposed at Nagasaki and Hiroshima, as reported by the National Research Council's Committee on the Biological Effects of Ionizing Radiation, was 1.89 excess cases per million person-rad-years of tissue dose (CBEIR80). This parameter was 7.0 at Rongelap and 17.8 at Utirik for the 10-year and older age grouping in 1974 (Co74).

badge data from a nearby military outpost (So55). Our external dose value at Sifo Island, 1.1. gray (110 rad) was greater than the 0.69 gray (69 rad) originally estimated by Sondhaus from post-evacuation surveys of exposure rate. The difference was due to the presence of very short-lived activation and transuranic nuclides which, according to the nuclide composition, must have been present during exposure at Sifo Island.

Medical observations concerning thyroid abnormalities have been tabulated along with the new thyroid dose estimated for each person. From these results, the mean cancer risk rate in the exposed population of 251 people was 150 thyroid cancers per million person-gray-years at risk ( $1.5 \pm 2.5$  thyroid cancers per million person-rad-years at risk). The mean time at risk for thyroid cancer was 19 years. The uncertainty derived for the estimate of risk was based on the standard deviation in adult mean urine activity concentration, the standard deviation in thyroid absorbed dose per unit intake, and the standard deviation in the spontaneous frequency of thyroid lesions in the unexposed comparison group.

In order to avoid unwarranted external and internal dose from the deposited radioactivity, the inhabitants of these atolls were relocated out of the affected area. They returned to Utirik in June 1954 and to Rongelap in June 1957. Environmental and personnel radiological monitoring programs were initiated in the mid 1950's by Brookhaven National Laboratory. The objective was to maintain a comprehensive radiological safety program. Post-return body-burden histories and activity-ingestion rate patterns were determined as were estimates of internal committed effective dose equivalent. External exposure rate and living pattern data were also collected. Relationships between body burden or urine activity concentration and a declining continuous intake scenario were developed in order to model retrospective and prospective dose equivalent. The dosimetric conclusions for the protracted exposure are summarized in Table 1 (Le84).

Table 1. Dosimetric conclusions for the protracted exposure of Rongelap and Utirik Adults from day of return to 50 years.

Nuclide	<u>Rongelap</u>	<u>Utirik</u>
	Committed Effective Dose Equivalent, Sv $\pm$ S.E.	Committed Effective Dose Equivalent, Sv $\pm$ S.E.
Fe-55	$4.8 \times 10^{-4} \pm 2.5 \times 10^{-4}$	$3.6 \times 10^{-4} \pm 2.0 \times 10^{-4}$
Co-60	$3.4 \times 10^{-4} \pm 1.3 \times 10^{-4}$	$4.4 \times 10^{-4} \pm 3.3 \times 10^{-4}$
Zn-65	$1.9 \times 10^{-3} \pm 1.0 \times 10^{-3}$	$3.0 \times 10^{-2} \pm 4.4 \times 10^{-2}$
Sr-90	$5.3 \times 10^{-4} \pm 8.0 \times 10^{-4}$	$1.0 \times 10^{-4} \pm 5.0 \times 10^{-5}$
Cs-137	$2.2 \times 10^{-2} \pm 1.1 \times 10^{-2}$	$1.3 \times 10^{-2} \pm 1.0 \times 10^{-2}$
External	$1.7 \times 10^{-2} \pm 3.4 \times 10^{-3}$	$4.1 \times 10^{-2} \pm 8.2 \times 10^{-3}$

A decline in the daily activity ingestion rate greater than that due solely to radioactive decay was estimated to be 9% per year for  $^{137}\text{Cs}$ , 8% per year for  $^{90}\text{Sr}$ , 80% per year for  $^{65}\text{Zn}$  and 60% per year for  $^{60}\text{Co}$ . A tentative value of 3% per year for Pu was estimated from sparse data. Current studies are aimed at determining the dosimetric impact of Pu. These values for the % per year decline in activity ingestion rate were observed at both atolls and do not account for the additional decline due to radioactive decay.

should not be extrapolated to other fallout exposures and 3) the medical observations quoted are not infallible, that is, a reevaluation of medical results may result in other cancer sites, different classifications for thyroid lesions or additional thyroid lesions.

The sources of information were many and varied. Discussions with persons initially involved, eg. Stan Cohn, Vic Bond, and Eugene Cronkite led to documents which have been cited in the reference section. A search for records at DOE headquarters led to the many files currently held by Tom McCraw. Mr. McCraw has acted as a repository for many Atomic Energy Commission documents. Some of these documents related directly to this study and were not easily located anywhere else. An abundance of environmental results have been published by the University of Washington's Laboratory of Radiation Ecology (also known as Applied Fisheries Laboratory). Medical information was published by Brookhaven National Laboratory's Medical Department and dietary information was published by both the Medical Department and the Safety and Environmental Protection Division. Much of the early and detailed observations about the accident were recorded in documents published by the U.S. Naval Radiological Defense Laboratory and by the naval Medical Research Institute.

The conclusions of the acute exposure study were that the population mean thyroid absorbed dose at Rongelap was 21 gray (2,100 rad). It was 6.7 gray (670 rad) at Sifo and 2.8 gray (280 rad) at Utirik. The overall thyroid cancer risk was in agreement with results published for Japanese exposed at Nagasaki and Hiroshima. The major route for intake of fallout was by direct ingestion. This resulted from outdoor food preparation and consumption practices during the period fallout clouds passed over the islands.

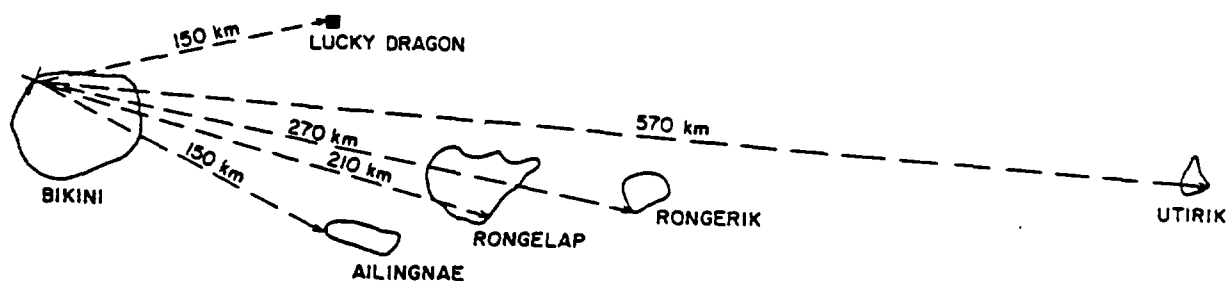


FIGURE 1. Relative location of the exposed people.

## SLIDE 2

Acute Exposure. In order to estimate acute exposure, meteorology and fallout dispersion models were used to calculate external exposure rate and air activity concentrations. Archival soil measurements were used to calculate surface activity levels of the iodine isotopes. The meteorology results and archival soil results were not used in the final thyroid dose estimate because they could not satisfy the basic criteria that new results must be related to previously known facts. Two approaches 1) the estimate of  $^{131}\text{I}$  intake from urine results and 2) the estimate of particle size and nuclide composition by Japanese scientists who examined fallout collected from a Japanese fishing vessel near Rongelap, could both be related to each other and be related to the known facts about fallout arrival and duration, external exposure rate measurements and gross beta measurements.

Once the nuclide composition was assessed, the composition was normalized to external exposure rate measurements. Exposure rate histories were constructed for each island. Estimates of intake of radioiodines and radiotelluriums were normalized to the  $^{131}\text{I}$  intake estimate which was based on Rongelap urine results and related to external exposure rate. The time and mode of intake were based on diet and living pattern observations. The population mean and individual thyroid absorbed dose were based on the age and location of the exposed people. Age dependent values of thyroid absorbed dose per unit activity intake were obtained from the scientific literature.

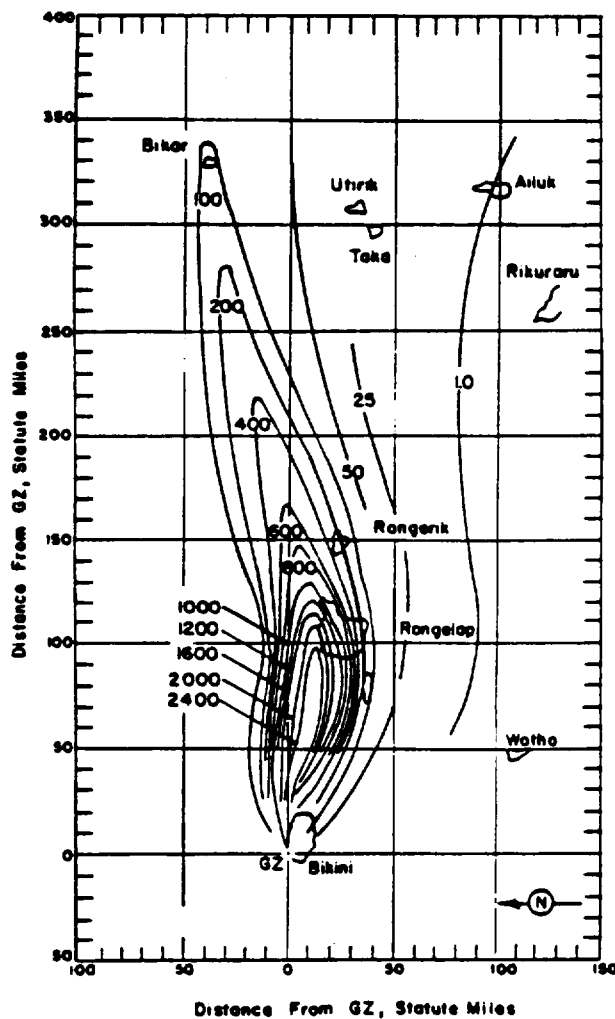
The final results were internal and external thyroid absorbed dose estimates for 251 exposed people.

### ACUTE EXPOSURE

Meteorology  
Archival Soil Measurements  
Composition of Fallout  
Activity Excreted  
Activity Intake  
Absorbed Dose

# SLIDE 4

BRAVO fallout patterns based on meteorology. This contour of exposure rate was estimated by the Armed Forces Special Weapons Project (AFSWP). The contour was cucumber shaped. Exposure rates were hypothetical values at one hour after the shot. The contaminated region was an area of more than 70,000 km<sup>2</sup> (27,000 square miles) extending 50 km (30 miles) upwind and over 540 km (340 miles) downwind. The width of the crosswind direction was variable, the maximum being over 220 km (140 miles).



Operation CASTLE - Shot 1 - Bravo.  
Off-site dose rate contours in r/hr at H+1 hour (AFSWP).

## SLIDE 6

Duration of fallout. Duration of fallout is defined as the time fallout begins up to the time of cessation. This should not be confused with the time fallout begins up to the time of evacuation which is much longer. Peterson's estimated duration of fallout of about 19 hours at Rongelap, appears to be too long relative to the known wind velocity moving the cloud past Rongelap (Cr56) and relative to the first-hand accounts of fallout duration given by the Marshallese evacuated from Rongelap Island (Sh57). Rongerik Atoll was 65 km (40 miles) further away from the detonation than was Rongelap Atoll. An upper limit of 16 hours duration at Rongerik Atoll was estimated by Sondhaus.

Fallout at the location of Sifo Island, Ailingnae Atoll was at the same distance from the detonation site as the Japanese vessel which was contaminated by BRAVO fallout. This fallout was named Bikini Ash by the Japanese. Bikini Ash granule size was visible to the eye (Su56) and was observed to fall for 5 hours (Ts55). Bikini Ash granule size is consistent with reports that fallout was visible at Rongelap, Rongerik and Ailingnae. Fallout would not have been visible at Utirik based on distance vs granule size extrapolations and fall velocity considerations. Visual observations of fallout arrival and cessation time were reported by many persons at each of these locations, (Sh57, Ts55) except Utirik, and were in reasonable agreement with Dunning's values. Lessard estimated duration time based on granule size of Bikini Ash, the relative positions of the atolls and the fishing vessel, and granule fall velocity estimates (Le84b).

## DURATION OF FALLOUT

Location of People	Distance from Ground Zero	Hours			
		1956 Sondhaus	1957 Dunning	1981 Peterson	1984 Lessard
Ailingnae	150 km	12	5.5	10	5
Rongelap	210 km	12	5.5	19	7
Rongerik	270 km	12	—	17	9
Utirik	570 km	12	17	3	19

## SLIDE 8

Estimates of airborne activity concentrations. Air activity concentration at Rongelap and Sifo Island were tabulated from the meteorology results provided by Peterson for  $^{131}\text{I}$  and  $^{133}\text{I}$  (Pe81). Also, results for air activity concentrations of  $^{131}\text{I}$  and  $^{133}\text{I}$  were estimated from the Bikini Ash composition and tabulated for comparison. Details on this method are given by Lessard (Le84b). The cumulated activity agree somewhat, however the instantaneous airborne activity concentrations do not agree well. In summary, the Peterson approach towards estimating dose to the exposed Marshallese requires further refinement in order to achieve correspondence with all available information regarding external exposure and exposure rate.

AIR ACTIVITY CONCENTRATIONS AT RONGELAP				
Time Post Detonation, Hours	1981, Peterson		1984, Lessard	
	$^{131}\text{I}$	$^{133}\text{I}$	$^{131}\text{I}$	$^{133}\text{I}$
5	7.4	250	3,700	110,000
7	250	7,400	1,100	25,000
10	15,000	110,000	19	330
14	74	1,500	0	0
17	11	250	0	0



SLIDE 10

Analysis of samples. Soil samples were analyzed for  $^{127}\text{I}$ ,  $^{129}\text{I}$ ,  $^{125}\text{Sb}$ ,  $^{137}\text{Cs}$ ,  $^{155}\text{Eu}$ , and  $^{60}\text{Co}$ . The methods used for neutron activation analysis were described by Brauer (Br74) and Keisch (Ke65). Iodine was separated from soils according to the method of Studier (St62). Once separated, the iodine was irradiated with neutrons in a nuclear reactor, purified to reduce levels of interfering nuclides and then measured by gamma spectroscopy (Br80). In order to perform quality control, comparison samples containing known amounts of  $^{125}\text{I}$ ,  $^{127}\text{I}$  and  $^{129}\text{I}$  were irradiated with each set of iodine samples isolated from Marshall Islands' soil.

Following irradiation the iodine samples were further purified and then precipitated onto the detecting media. The number of atoms of activated nuclide were determined by gamma spectroscopy measurements of the radioactivity produced in the soil sample and in a comparison sample. The number of initial comparison atoms and resulting comparison activity were used to determine a production ratio. The production ratio was applied to the soil sample activity and the number of atoms of activated nuclide per gram of soil was estimated. Corrections to the soil activity were made based on results for soil sample blanks, comparison sample blanks and method yield. Individual counting errors were normally less than 5% although a few samples approached 20%. A least squares fitting was performed on results for nuclide soil activity per unit soil mass vs days post detonation using linear, exponential, logarithmic and power function models. Sample results varied from their best fit value by as much as a factor of 9 and by an average factor of 2.5 over the period 1955 to 1977.

The best fitting function was determined based on a comparison of the coefficient of determination for each model. Functions used with  $^{129}\text{I}$  results for Rongelap soil are plotted here. For  $^{129}\text{I}$  soil results, the best fitting function was exponential. All four fitting functions were generally useful in predicting soil activity per gram at times after 600 days post BRAVO for all nuclides. Significant departure between functions occurs during the period several hours out to one year post BRAVO. For example, at 0.5 days the difference between the exponential and power function estimates spans 5 orders of magnitude for  $^{129}\text{I}$ .

## SLIDE 11

Ratio of nuclide to total fallout activity. The ratio of  $^{129}\text{I}$  activity to total fallout activity would help in determining if the archival soil analysis for radioiodine corresponded to other measured or hypothetical ratios. The surface-soil activity of each nuclide measured by Brauer was estimated for 0.5 days post detonation. This was the assumed time of cessation of fallout at Rongelap. The value for the nuclide activity per unit mass of soil at the cessation of fallout was estimated from the best fit of archival soil results. The value of the denominator used in the ratio was based on measured gross beta activity. Gross beta analysis was done on soil samples taken on March 8, 1954 (OC68) from Rongelap Atoll.

Hypothetical nuclide activity relative to total fission product activity was estimated from data on thermonuclear fission of  $^{238}\text{U}$  given by Crocker (Cr65). Total activity values given by Crocker do not account for chemical and physical deletion or enhancement of fission products, production of activation products or production of transuranics. Total activity per 10,000 fissions at 0.5 days was taken from Table 3 of Crocker's report (Cr65). Individual nuclide activities were calculated by Crocker's methods and the original input data (Cr63).

The ratio derived from BRAVO fallout measurements was based on Bikini Ash activity.

For  $^{125}\text{Sb}$ , the ratios were not similar however sample size was small. For  $^{155}\text{Eu}$  and  $^{137}\text{Cs}$ , results were in accord at both Rongelap and Utirik. The archival soil results for  $^{129}\text{I}$  at Rongelap and Utirik were distinctly different from the thermonuclear fission results and Bikini Ash results.

---

SURFACE ACTIVITY RATIOS 0.5 DAYS  
POST DETONATION

---

Nuclide	Archival Soil Measurements	BRAVO Fallout Measurements	Hypothetical Thermonuclear Fission $^{238}\text{U}$
	Nuclide Activity Gross Beta Activity	Nuclide Activity Bikini Ash Beta Activity	Nuclide Activity Fission Product Activity
$^{125}\text{Sb}$	$1.8 \times 10^{-7}$	$3.5 \times 10^{-6}$	$4.6 \times 10^{-6}$
$^{129}\text{I}$	$2.6 \times 10^{-10}$	$4.5 \times 10^{-12}$	$3.5 \times 10^{-12}$
$^{137}\text{Cs}$	$7.6 \times 10^{-6}$	$7.1 \times 10^{-6}$	$5.5 \times 10^{-6}$
$^{155}\text{Eu}$	$8.3 \times 10^{-7}$	$7.1 \times 10^{-7}$	$9.6 \times 10^{-7}$

---

SLIDE 13

Analysis of BRAVO fallout. Bikini Ash fell on the Japanese fishing vessel, the 5th Lucky Dragon, on the day of the test. Its gross beta activity was measured and standardized to day 26, and individual nuclide beta-activity was identified and quantified by Japanese scientists (Ya56, Ts55).

The studies by Suito, Takiyama and Uyeda (Su56) indicated Bikini Ash consisted of irregularly shaped white granules. Bikini Ash, taken from the deck of the 5th Lucky Dragon, was deposited while the ship was located about 150 km (90 miles) from the detonation site (Ta55). From the size and shape distribution it was determined the mean volume diameter of Bikini Ash granules was  $320 \mu\text{m} \pm 70 \mu\text{m}$  (Su56). The mean volume diameter was defined by them as the diameter corresponding to the mean volume. The mean mass of a granule was 0.039 mg (Su56). The specific gravity was 2.4 (Su56), less than the specific gravity of  $\text{CaCO}_3$ , 2.7-2.9. The granules were aggregates of smaller unit particles with shapes that varied from spindles to cubes to spheres (Su56). The size of these smaller unit particles making up the granules varied from 0.1 to  $3.0 \mu\text{m}$  (Su56). It was suggested by Suito that Bikini Ash was formed by evaporation of the coral reef to its constituent atoms and then by recrystallization of Ca with  $\text{H}_2\text{O}$  and  $\text{CO}_2$  in the air.

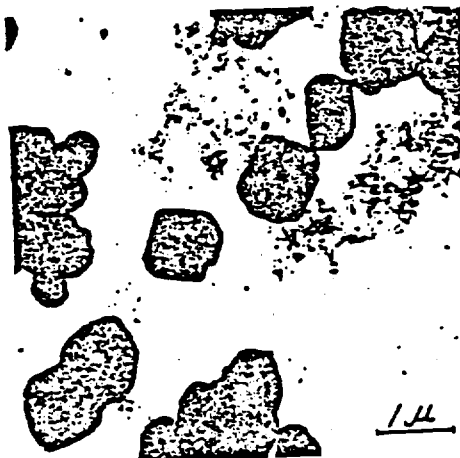
---

ANALYSIS OF BRAVO FALLOUT

---

CaO	55%
MgO	7%
CO <sub>2</sub>	12%
H <sub>2</sub> O	26%

---



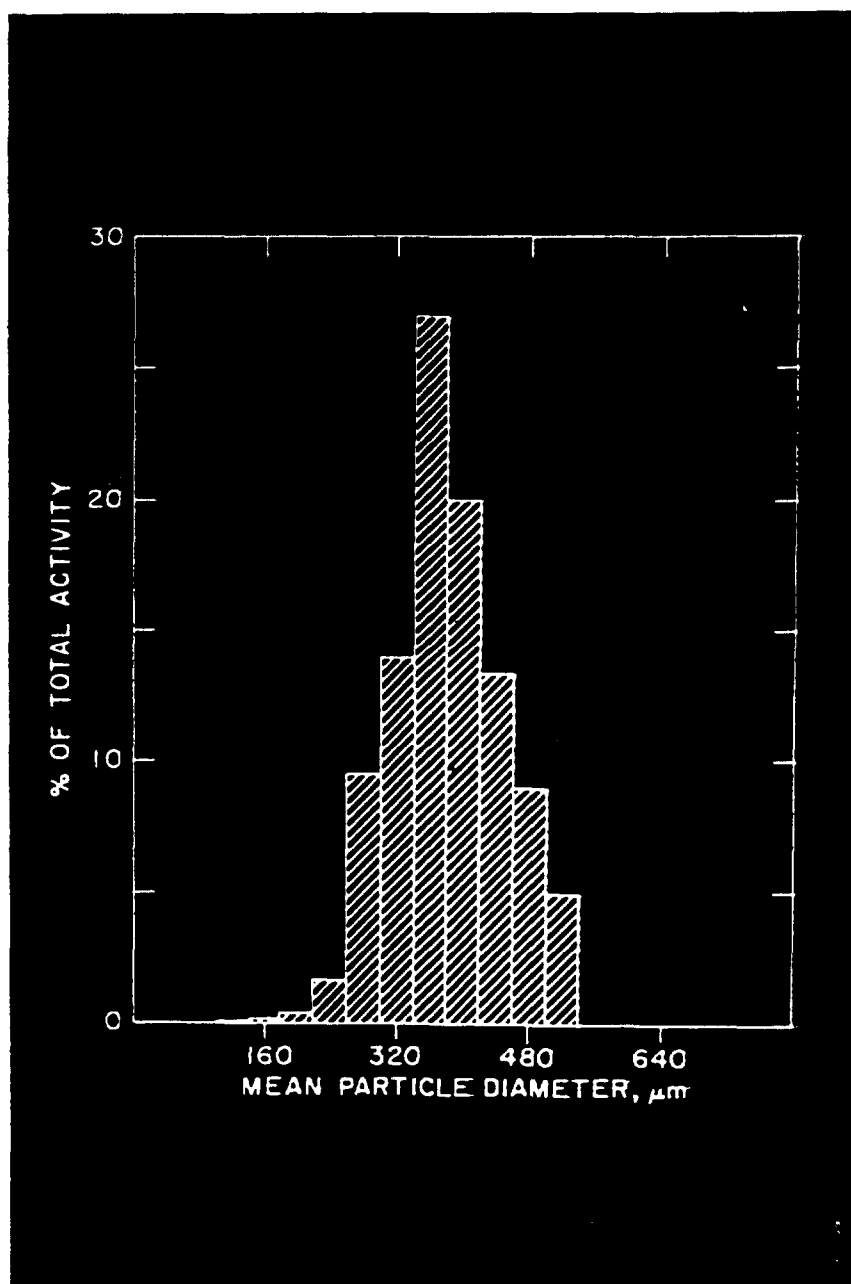
---

Microscopic Detail of BRAVO Fallout

---

# SLIDE 15

Granule size distribution and activity. The granule size distribution of Bikini Ash was used to estimate the time over which the bulk of the activity fell on the fishing vessel. Larger volume granules carried a major portion of the activity which fell at early times post detonation (La65). The Bikini Ash activity versus granule size distribution in % of total activity as a function of granule size was plotted here. In order to construct this histogram, the activity of a granule was assumed proportional to the 3.5 power of its size. Lavrenchik reported measurements varied such that the activity of a granule was proportional to the 3rd or 4th power of the size (La65). A generalization observed by him was that the activity and volume were proportional. The number of granules in each size class was taken from Suito (Su56). The size at median activity was  $370\mu\text{m}$  for Bikini Ash.



# SLIDE 17

BRAVO fallout characteristics. The effect of fractionation on decay rate is very complex and simple observation of overall radioactive decay does not yield significant information. Even so, the decay rate from widely distributed samples obtained out to 500 km (300 miles) from the BRAVO detonation site were similar as were the decay rates from activity on different size fallout granules collected at the same site (OC68). These facts alone may not be used to indicate the same fractionation was common to all granule sizes. In fact, small granules traveled with the cloud for longer periods of time and possible adsorbed more longer-lived nuclides than did the very large granules.

In the forthcoming analysis, the fractionation observed for Bikini Ash granules was assumed to be similar for granules at Rongelap, Sifo and Utirik Islands. With the possible exception of Utirik Island, this was considered a valid assumption due to the proximity of Rongelap and Sifo islands to the 5th Lucky Dragon. The granule size distribution was assumed to have the same shape as Bikini Ash as given by Suito (Su56). Assuming the activity of a granule was proportional to the 3.5 power of the size of the granule (La65), the per cent of total activity versus granule size was estimated. The size at median activity is given here for each location. Granules of a given size were spread throughout the stem, the base of the cloud and up to the cloud top at 40 km (24 miles). In fact, the entire distribution of granule sizes would reach the surface at any point in time, not just one size at one time. The simple model was assumed here for the purpose of estimating the rate of rise of exposure rate, the rate of accumulation of activity at the surface, and accumulated internal exposure during the period of rising exposure rates. This period was very short relative to the total exposure interval. The simple model was in agreement with measurements of rate of rise of exposure rate for weapons tests made during the Hardtack Series in 1957 (USPHS57) and with the rate of rise of exposure rate measured for one-half hour at Rongerik Atoll on March 1, 1954 (So55).

## BRAVO FALLOUT CHARACTERISTICS

Location	Size At Median Activity $\mu\text{m}$	Distance From Ground Zero km
5th Lucky Dragon	370	150
Rongelap Island	150	210
Sifo Island	370	150
Utirik Island	15	570
Specific Gravity : 2.4 Solubility : 20-50% Iodine in Seawater Relative Activity : (Size/Largest Size) <sup>3.5</sup> Unit Particle Size : 0.1 - 3 $\mu\text{m}$		

# SLIDE 19

Normalization of fallout activity to exposure rate. Beck recorded activity per unit area per unit exposure rate factors for a number of particulate gamma-emitting fission products and for a number of particulate activation products and residual nuclear materials as the ground as a result of weapons tests (Be80). The exposure rates at one meter above the surface of a planar source of unit area of Bikini Ash activity were calculated for each nuclide based on the data of Beck (Be80) and nuclide composition of the ash.

By summing the product of each nuclide's exposure rate (relative to unit activity per unit area) and fraction of total activity represented by each nuclide in Bikini Ash, the exposure rate from Bikini Ash per unit areal activity was estimated to be  $1.12 \times 10^{-17} \text{ C kg}^{-1} \text{ s}^{-1} \text{ Bq}^{-1} \text{ m}^2$  ( $5.8 \times 10^{-3} \text{ R h}^{-1} \text{ mCi}^{-1} \text{ km}^2$ ). By inverting this sum and multiplying by the fraction of each nuclide activity relative to the total Bikini Ash activity and the Rongelap exposure rate on day 26, we estimated the beta activity of each nuclide per unit area due to BRAVO fallout on the surface of Rongelap Island.

The estimates of mean unweathered activity per unit area due to BRAVO fallout on Rongelap Island were extrapolated back to 0.5 days post detonation. The 0.5 day post detonation time was chosen by us as the point in time at which the fallout at Rongelap Island had effectively ceased (Sh57). First order linear kinetics for serially related nuclide species (Ba10, Sk75) and decay schemes from Table of the Isotopes (Le78) were used to calculate the 0.5 day activity from the day 26 activity. The mean unweathered activity per unit area for any short-lived precursor nuclide, not present on day 26 but on the ground at the end of fallout at 0.5 days, was also calculated.

---

## AREAL ACTIVITY RELATED TO EXPOSURE RATE

---

$$\sum \frac{(R \text{ h}^{-1})_{\text{Nuclide}}}{(\text{Ci m}^{-2})_{\text{Nuclide}}} \times \frac{(\text{Ci})_{\text{Nuclide}}}{(\text{Ci})_{\text{Bikini Ash}}} = \frac{(R \text{ h}^{-1})_{\text{Bikini Ash}}}{(\text{Ci m}^{-2})_{\text{Bikini Ash}}}$$


---

$$\frac{(\text{Ci m}^{-2})_{\text{Bikini Ash}}}{(R \text{ h}^{-1})_{\text{Bikini Ash}}} \times (R \text{ h}^{-1})_{\text{Measured}} \times \frac{(\text{Ci})_{\text{Nuclide}}}{(\text{Ci})_{\text{Bikini Ash}}} = (\text{Ci m}^{-2})_{\text{Nuclide}}$$


---

# SLIDE 21

Radioactivity intake estimated from excreta. The fraction of an initial  $^{131}\text{I}$  activity intake by ingestion that would be eliminated by an adult on a given day post the intake was calculated by two methods. One was a model by Johnson (Jo81) and the other was a model used by ICRP (ICRP79). Both models had feedback incorporated into the estimate of the fraction of initial intake. Both were solved using catenary compartment kinetics and both led to similar values for elimination of  $^{131}\text{I}$  by a reference man. Based on 0.48 kBq ( $1.32 \times 10^{-2} \mu\text{Ci}$ ) in adult urine on the 17th day post intake, a 3,440 kBq ( $93 \mu\text{Ci}$ ) intake was estimated for  $^{131}\text{I}$ .

The intake of 3,440 kBq ( $93 \mu\text{Ci}$ ) was used as a normalization point. That is, once the relationship between  $^{131}\text{I}$  and other nuclides in fallout was determined by us, then the contribution to thyroid dose from all radioiodines was estimated while keeping the  $^{131}\text{I}$  intake at 3,440 kBq ( $93 \mu\text{Ci}$ ).

Whole-body retention functions were given by ICRP (ICRP72) for strontium and barium as follows:

$$R_{\text{Sr}}(t) = 0.60e^{-0.25t} + 0.299(t+0.20)^{-0.18}(0.555e^{-6.5 \times 10^{-5}t} + 0.445e^{-2.6 \times 10^{-4}t}),$$

$$R_{\text{Ba}}(t) = 0.38e^{-0.75t} + 0.191(t+0.007)^{-0.237}(0.564e^{-1.09 \times 10^{-4}t} + 0.436e^{-4.36 \times 10^{-4}t}),$$

where  $t$  is in days and  $R(t)$  is the absorbed fraction remaining on day  $t$ . The fecal to urine ratios for excretion of absorbed Sr and Ba were 0.25 and 9.0, respectively (ICRP72). Correcting for 45 days of decay, the  $^{89}\text{Sr}$  activity absorbed was estimated to be  $2.3 \times 10^4$  Bq ( $0.62 \mu\text{Ci}$ ) and the  $^{140}\text{Ba}$  activity absorbed was  $6.1 \times 10^5$  Bq ( $16.4 \mu\text{Ci}$ ). If fallout was directly ingested as a single intake of dust at 0.5 days post detonation, then the intake of  $^{140}\text{Ba}$ ,  $^{90}\text{Sr}$  or  $^{131}\text{I}$  should be in a ratio similar to one estimated by us by a different approach. The fraction of ingested iodine absorbed into blood was taken as 1.0, the fraction of ingested strontium absorbed into blood was taken as 0.2 and the fraction of ingested barium absorbed into blood was taken as 0.06 (ICRP68). The intake ratios we obtained from urine results for  $^{131}\text{I}$  relative to  $^{89}\text{Sr}$  or  $^{140}\text{Ba}$  are 28 and 0.34, respectively. The hypothetical ratios are 8.5 and 1.2 based on unfractionated thermonuclear fission data. Thus the urine derived ratio of activity is a factor of 3 lower than the hypothetical ratio for  $^{89}\text{Sr}$  and a factor of 3 higher for  $^{140}\text{Ba}$ .

## ESTIMATE OF ACTIVITY INGESTED (RONGELAP)

Nuclide	Activity Ingested Bq	Iodine Activity*
		Nuclide Activity
$^{131}\text{I}$	$3.4 \times 10^6$	1.0
$^{89}\text{Sr}$	$1.2 \times 10^5$	8.5
$^{140}\text{Ba}$	$1.0 \times 10^7$	1.2

\*Thermonuclear neutron fission and 5 hours post detonation.

and indicates to us that direct ingestion of fallout was a reasonable pathway to assume.

Although BRAVO debris was not highly soluble in water, calcium carbonate and hydrated calcium oxide (the matrix in which BRAVO fallout was entrained) were both highly soluble in acid (Co72). Therefore, ingestion of BRAVO debris resulted in release of radioiodines trapped in the granules due to the acid environment of the stomach. The mass and volume of BRAVO fallout granules were insignificant relative to the normal amount of food eaten per meal, the normal amount being about 400 g for adult meals (Ev66). The mass of BRAVO fallout per  $m^2$  at Rongelap Island was 4.4 g. The volume corresponding to this mass was  $1.9 \text{ cm}^3$ , about four tenths the volume of a teaspoon. The mass per  $m^2$  and corresponding volume at Utirik Island was 0.46 g and  $0.20 \text{ cm}^3$ . For Sifo Island it was  $1.5 \text{ g m}^{-2}$  and  $0.48 \text{ cm}^3 \text{ m}^{-2}$ . These mass and volume per unit area estimates were for the point in time at which all fallout was on the ground. The values for Utirik and Sifo Islands were estimated by ratio of the exposure rate to that at Rongelap Island with the ratio being estimated after the cessation of fallout.

The main water supplies at Rongelap, eight cisterns, each contained a height of 0.23 m of water during the later part of March and early April 1954 (Sh57). Water was drawn from six of these cisterns at Rongelap for gross beta analysis on March 2, 1954 (see report of the radsafe team, USS PHILIP, OC68), and one other cistern was reported as out. Each cistern opening was about  $0.65 \text{ m}^2$  and was fed by galvanized metal sheeting used for catching rainwater (Sh57). A little rain was reported on the afternoon of March 1, 1954 (Sh57). It was assumed that the additional cistern catchment area did not contribute water or activity to the cistern. Results of the analysis for gross beta activity concentration in cistern water ranged from  $1.8 \times 10^5$  to  $2.0 \times 10^6 \text{ Bq l}^{-1}$  ( $0.005$  to  $0.054 \mu\text{Ci ml}^{-1}$ ) with a mean of  $5.0 \times 10^5 \text{ Bq l}^{-1}$  ( $0.027 \mu\text{Ci ml}^{-1}$ ) at 50 hours post detonation (OC68). The fallout from Castle series coral surface bursts including BRAVO was barely soluble in water (Ka66). Estimates of solubility were based on BRAVO fallout which was collected with mixtures of rain and sea spray, 20-50% of the iodine activity was found in the liquid phase (Ka66). The servicemen at Rongerik Atoll examined the terrestrial fallout under a microscope and reported that the sand like granules were not soluble in water on the microscope slide (Sh57). Therefore, most BRAVO activity probably remained with fallout granules at the bottom of a cistern.

Mean air concentration estimates of the activity of selected nuclides were based on the deposition rates of fallout granules and total activity deposited. The air activity concentration at a point in time was assumed 1) directly proportional to the fraction of total activity deposited per minute, 2) directly proportional to the total activity on the ground at the end of fallout (decay corrected back to that point in time) and 3) inversely proportional to fall velocity of granules. The cumulated air activity concentrations for Rongelap Island which were derived by us from Bikini Ash activity results were about three times less than the cumulated air activity concentrations given by Peterson (Pe81).







SLIDE 27

Estimated activity intake from cistern water. Based on 1) Bikini Ash radioiodine activity per unit area estimates, 2) a 20% release of iodine activity from fallout granules to cistern water and, 3) an average cistern water volume of 0.15 m<sup>3</sup>, the radioiodine activity concentrations were estimated for cisterns located at Rongelap Island. These concentrations were in agreement with gross beta analysis of cistern water.

Prior to evacuation of Rongelap, many weeks of drought were reported by Sharp (Sh57). In the weeks preceding the BRAVO contamination, water from cisterns was rationed to one pint cup per person each day (Sh57). Assuming this wording implies US liquid measure, then 470 cm<sup>3</sup> of water per person per day were distributed and regulated by village officials. This water was used to make tea and coffee and was directly ingested (Sh57). One hundred fifty cm<sup>3</sup> of water were assumed to be taken with each meal. At Rongelap Island, this was assumed to occur at 5.5 (lunch), 12 (dinner), 24 (breakfast), 30 (lunch), 38 (dinner) and 50 (breakfast) hours post detonation.

These assumed cistern water intakes led us to estimate the ingested activity tabulated here. This was a conservative estimate of radioiodine activity intake from this pathway because all the activity in the liquid phase in the cistern was assumed to be due only to the iodine isotopes.

---

ESTIMATED ACTIVITY INTAKE FROM  
CISTERN WATER

---

Rongelap Island

---

Nuclide	Activity Intake <sup>a</sup> , M Bq
<sup>135</sup> I	0.75
<sup>134</sup> I	0.14
<sup>133</sup> I	1.0
<sup>132</sup> I	0.41
<sup>131</sup> I	0.078

---

<sup>a</sup>Normalized to exposure rate and fallout composition.

---

## SLIDE 29

Activity intake by inhalation. Airborne activity intakes were dependent upon the breathing rate of individuals during fallout cloud passage. Breathing rate was assumed proportional to body mass. We arrived at this conclusion based on reference data given by ICRP for persons less than 58 kg (ICRP74). Adult reference values for breathing rates (ICRP74) were assumed for all Marshallese adults regardless of body mass. At Rongelap Island, BRAVO debris passed during the afternoon, a period of light physical activity for the population. At Utirik Island, the debris passed during the night, a period of resting. At Sifo Island a period of light physical activity was assumed in order to estimate breathing rate during the morning they were exposed. On the basis of urine results and breathing rate, it was determined that inhalation could not account for the estimated activity intake for  $^{131}\text{I}$ . Less than 1% of the intake could be attributed to inhalation. In fact lethal external exposure rates would have to accompany significant radioiodine intakes if inhalation was assumed to be the dominant intake pathway leading to the urine activity excreted on day 17.

## ESTIMATE OF INHALED ACTIVITY\*

	Body Weight kg	KBq						
		$^{135}\text{I}$	$^{134}\text{I}$	$^{133}\text{I}$	$^{132}\text{I}$	$^{131}\text{I}$	$^{132}\text{Te}$	$^{131\text{m}}\text{Te}$
Rongelap Adult Male	70	890	370	410	97	18	110	20
Rongelap Child	30	520	220	240	55	10	59	12
Utirik Adult Male	70	70	—	1200	410	78	410	59
Utirik Child	30	41	—	700	230	44	230	35
Sifo Adult Male	70	81	85	85	4.4	0.85	5.5	1.1
Sifo Child	30	48	48	48	2.5	0.48	3.2	0.59

\* Air concentrations normalized to exposure rate measurements and fallout composition.

## SLIDE 31

Absorbed dose estimates. External thyroid absorbed dose estimates were based on integrated photon exposure and based on an adjustment for living pattern in a variable exposure rate environment.

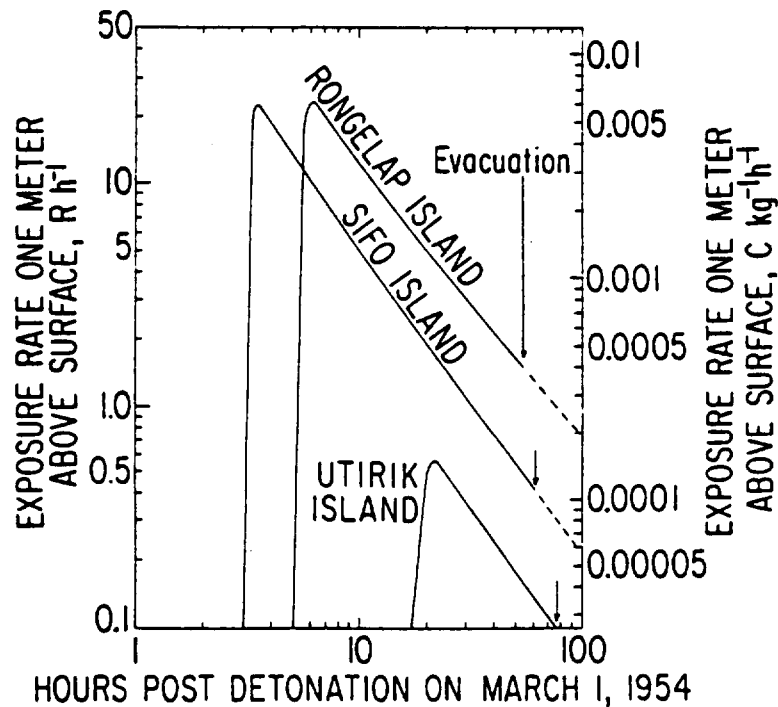
External beta radiation penetrating to the depth of the thyroid was not thought by us to be important. The thickness of tissue overlying the thyroid ranges from 0.4 to 2.0 cm (0.2 to 0.8 in), average 0.82cm (0.3 in), and does not correlate with age or body weight very well (ICRP74). The minimum beta energy for penetration of 0.82 cm (0.3 in) of tissue was estimated to be 1.8 MeV. At Rongelap Island about 70% of the population had skin lesions on some part of the neck appearing about 21 days post exposure (Cr56). This would imply a skin surface dose of tens of gray (several thousand rad). Only a small per cent of the beta flux was above 1.8 MeV in kinetic energy. Of this higher energy flux, only a small fraction would penetrate 0.82 cm (0.3 in) of tissue and deposit energy in the thyroid. Thus thyroid dose from this pathway was considered insignificant.

For internal emitters, thyroid absorbed dose per unit intake was compiled from values generated by Johnson (Jo82). An exponential interpolation of non-adult values was performed. Thyroid absorbed dose commitment was calculated because the nuclides of interest had half-lives much shorter than 50 years. Absorbed dose was generated based on the assumption of a quality factor of one. The absorbed dose per unit activity intake values for adults were those given by Johnson directly (Jo82). The values for the tellurium isotopes were generated from reference man data contained in Limits for Intakes of Radionuclides by Workers (ICRP79). Tellurium isotope values for the ages less than adult were generated by ratio of the Johnson values for the appropriate iodine daughters. The thyroid absorbed dose for any age per unit intake of any tellurium isotope was assumed directly proportional to the product of the adult value and the ratio of the iodine value.

## ABSORBED DOSE ESTIMATES

## SLIDE 33

External exposure rate. Rate of rise in exposure rate at Rongerik Atoll was measured by a monitoring instrument for one-half hour. A best fit of the results yielded an exponential rate of rise in exposure rate. The exposure rate peaked within an hour after the arrival of fallout at Rongelap and Sifo Islands. Arrival time and peak exposure rate were estimated by us based on granule size considerations and the rate of activity deposition. The estimate of rate of rise was in agreement with the rate of rise observed at Rongerik. The exposure rate peaked within 3 hours at Utirik. Decline of exposure rate was based on the decay of 142 nuclides which precursed the Bikini Ash. The exposure rate histories at Rongelap, Utirik and Sifo Islands were normalized to the results of the radSAFE survey teams of the USS PHILIP and USS RENSHAW (OC68). The mean exposure rate at Rongelap was estimated to peak at  $5.7 \times 10^{-3} \text{ C kg}^{-1} \text{ h}^{-1}$  ( $22 \text{ Rh}^{-1}$ ). At Utirik the peak was  $1.5 \times 10^{-4} \text{ C kg}^{-1} \text{ h}^{-1}$  ( $0.59 \text{ Rh}^{-1}$ ) and at Sifo  $5.2 \times 10^{-3} \text{ C kg}^{-1} \text{ h}^{-1}$  ( $20 \text{ Rh}^{-1}$ ). After the cessation of fallout the exposure rate ratio between Rongelap and Sifo Islands was 3.0 to 1.0 and between Rongelap and Utirik Islands, 9.5 to 1.0.



## SLIDE 35

Internal thyroid absorbed dose. The product of age specific intake and age specific thyroid absorbed dose per unit intake was compiled for different hypothetical ages. These results were applied to the age and location of persons exposed during the acute phase and doses to population groups are listed here. The thyroid absorbed dose from all iodine and tellurium nuclides as 7.7 times the dose due to  $^{131}\text{I}$  at Rongelap Island for adults. It was 10 times the dose due to  $^{131}\text{I}$  at Sifo Island and 4.7 times the dose due to  $^{131}\text{I}$  at Utirik Island. The most probable ingestion dose evaluation by James (Ja64) for a 3.5 year old Rongelap girl was given as 14.45 gray (1,445 rad). James assumed the total thyroid absorbed dose from ingestion of all iodine isotopes in fallout was 2.6 times the thyroid dose due to  $^{131}\text{I}$ . This factor is dependent upon the age of the fallout and the age of the individual and differs from ratios given here by us. Since James based the total thyroid dose on  $^{131}\text{I}$  measurements in urine and this factor of 2.6, a significant difference in thyroid dose derived from the Bikini Ash method versus the James method occurs.

Several methods were used to estimate a range of fallout material ingested. One was to ingest known quantities of drug grade  $\text{CaCO}_3$  with meals and subjectively arrive at similar descriptions of taste as given by the Rongelap people at the time of evacuation in March, 1954. A group of five adult white males at BNL reported that 200 mg of  $\text{CaCO}_3$  when mixed with food, could not be sensed by taste at all. About 70 mg per meal were assumed to be ingested for the mean dose estimate. Another method to estimate a range of dose was to assume the range associated with the weight of the contents of the stomach in cases of sudden death (Ev66). This range, 0 to 380 grams, mean 82 grams, implies a maximum intake of about 5 times the mean value. Another method was to examine the range of  $^{137}\text{Cs}$  daily activity intake from 1957 to 1983 for Rongelap and Utirik people. The intake rate was estimated from whole-body counting results. The range of  $^{137}\text{Cs}$  intake rate was about 5 times the mean value (Le84). Another method was to examine the range of  $^{137}\text{Cs}$  body burdens exhibited by the population inhabiting Bikini Island from 1974 to 1978 (Mi83). The range was 3.2 times the mean value. Based on the above range considerations, a value of 4 times the intake and thus 4 times the mean thyroid absorbed dose was assumed by us for estimates of maximum thyroid dose.

Age at Exposure	Total Number	External Whole Body Dose Gray	Internal Emitter Thyroid Dose Gray	Internal Emitter Dose $^{131}\text{I}$ Dose
<b>RONGELAP</b>				
<i>In Utero</i>	3	1.9	4.5	8.1
<10	21	1.9	38	8.3
10-18	12	1.9	15	7.7
>18	31	1.9	11	7.7
<b>SIFO</b>				
<i>In Utero</i>	1	1.1	5.0	11
<10	7	1.1	9.9	11
>18	11	1.1	3.0	10
<b>UTIRIK</b>				
<i>In Utero</i>	8	0.11	1.2	4.9
<10	56	0.11	4.8	4.9
10-18	19	0.11	2.1	4.8
>18	84	0.11	1.5	4.7

During the rehabilitation and repopulation years, the medical services provided by R.A. Conard and the Brookhaven Medical Team at Rongelap and Utirik were expanded to include sick call and body burden measurements at Bikini. Body burden measurements were made in 1974 (Co75) and in 1977 (Co77). In August 1977, the responsibility for providing body burden measurements was transferred from the Medical Department to the Safety and Environmental Protection Division of BNL. The 1978 and 1979 body burden measurements of the Bikini population were conducted by the latter organization.

In August 1978, the Bikini people were relocated to Kili Island and Majuro Atoll following increasing body burdens of  $^{137}\text{Cs}$ . Removal of the Bikini population from Bikini Atoll eliminated the  $^{137}\text{Cs}$  source term from the diet and limited the dose equivalent received by this population.

The scheduling of the first Enewetak nuclear test necessitated the removal of the people in 1947. On December 3, 1947 the Governor of the Marshalls flew to Enewetak and proposed to the chiefs that they move to Ujelang Atoll, which was then being prepared as a relocation site for the Bikini people. The two chiefs, Johannes and Abraham, were flown to Ujelang on December 4th and later returned to Enewetak after selecting sites for dwellings and community buildings. Temporary living quarters were ready for the people of Enewetak when they went to Ujelang on December 21, 1947. Permanent facilities on Ujelang were constructed in the spring of 1948.

On May 28, 1948 resettlement was completed. The first three nuclear test, the Sandstone series, were completed by May 14, 1948 and no additional tests were conducted at Enewetak until 1951. The last test was completed in July 1958.

In September 1974, the people of Enewetak and their advisors returned to Enewetak for a meeting with representatives from the Defense Nuclear Agency, the Department of the Interior, and the Atomic Energy Commission. The purpose of the meeting was to present the draft environmental statement regarding the proposed project to rehabilitate the atoll, and to return the former residents there.

In February 1980, members of the BNL Marshall Islands Radiological Safety Program conducted a field trip to Japtan and Enewetak Islands, Enewetak Atoll and Ujelang Island, Ujelang Atoll. The purpose of this trip was to obtain baseline radionuclide body burden data on the Enewetak population prior to the repatriation in April 1980. The people of Enewetak repatriated the islands on the southern part of the atoll. Certain northern locations of the atoll have been off limits except for short visits. Most of the food is imported at this time. Monitoring of inhabitants has occurred on an annual basis since the people's return.



## SLIDE 37

Protracted exposure. The protracted exposure of the Marshallese occurred after people returned to the contaminated areas. The people of Utirik and Rongelap returned to a post accident environment involving radioactivity from one detonation. The people of Bikini and Enewetak Atolls returned to a post testing environment involving radioactivity from many tests occurring from 1946 to 1958. In order to assure the people that radiation exposure guidelines were being followed, routine bioassay missions have been undertaken since these people returned to their homes. Additionally, diet and living pattern studies, where scientists lived with the people for extended periods of time were undertaken to understand the internal and external exposure patterns. Information from the bioassay missions and other studies have been reviewed and estimates of radioactivity intake and corresponding dose equivalent have been made (Le84).

### PROTRACTED EXPOSURE

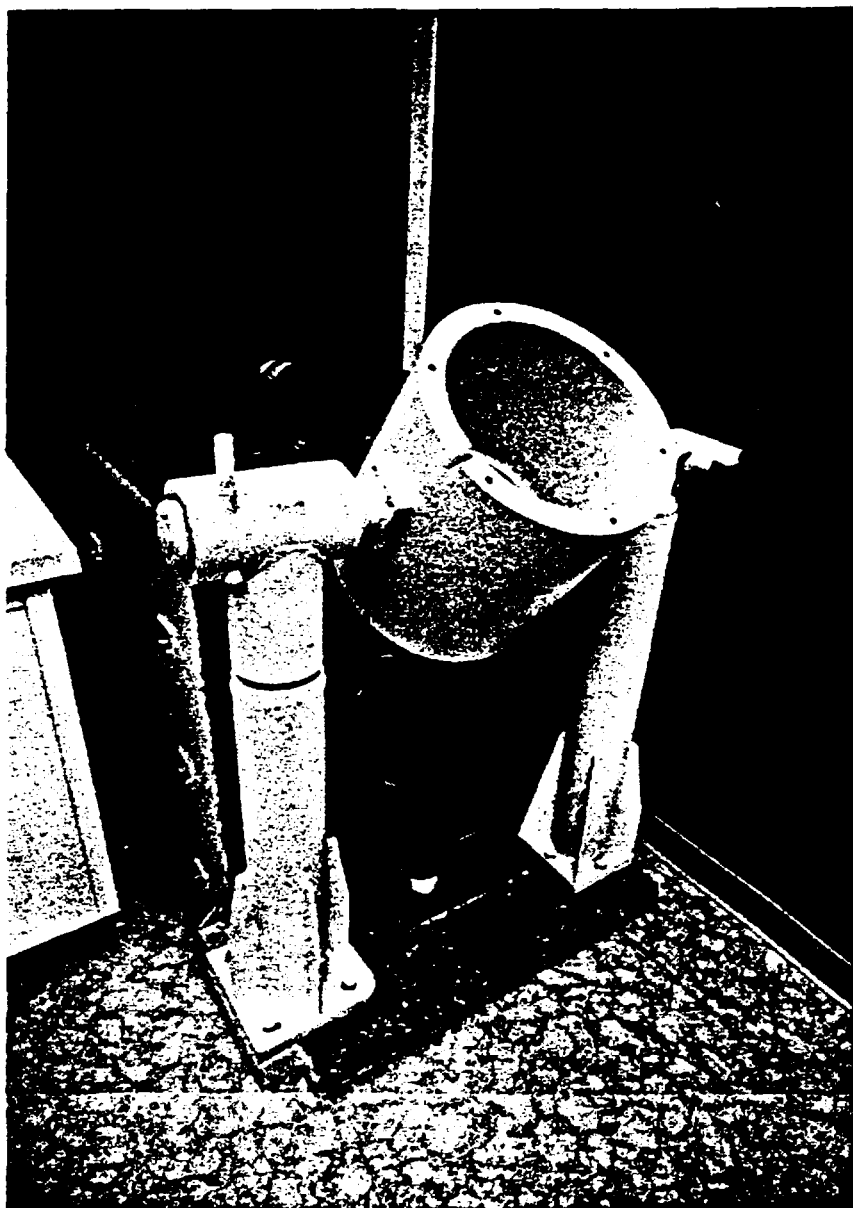
---

Field Measurements  
Diet and Living Patterns  
Body Burden Histories  
Intake Estimates  
Committed Effective Dose Equivalent

SLIDE 39

Whole-body counter. The detector chosen for field use by Brookhaven personnel was a 28 cm diameter, 10 cm thick, sodium iodide thallium activated scintillation crystal NaI(Tl). It is optically coupled to three low background magnetically shielded photomultiplier tubes connected in parallel through a summing box with the combined output routed to an amplifier and then to a microprocessor-based computer and pulse height analyzer (PHA). The PHA data is stored on a magnetic discette, and results are analyzed in the field and at BNL using a matrix reduction, minimization of the sum of squares techniques.

The gamma emitting nuclides observed have been  $^{65}\text{Zn}$ ,  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$  and  $^{207}\text{Bi}$ . Additionally, naturally occurring  $^{40}\text{K}$  is present in normal amounts. A typical counting time is 15 minutes and a typical minimum detection limit is 100 Bq (3 nCi). The whole-body counting system is currently standardized against a human like phantom.



SLIDE 41

External exposure measurements. In April 1975, BNL personnel initiated an external survey of Bikini Atoll in order to obtain information concerning the ambient external radiation levels resulting from the mid 1950's weapons testing program and to make dose equivalent determinations for the individuals living in the surveyed area. From 1975 to 1977, measurements were made to provide sufficient information on the external exposure received by the Marshallese people.

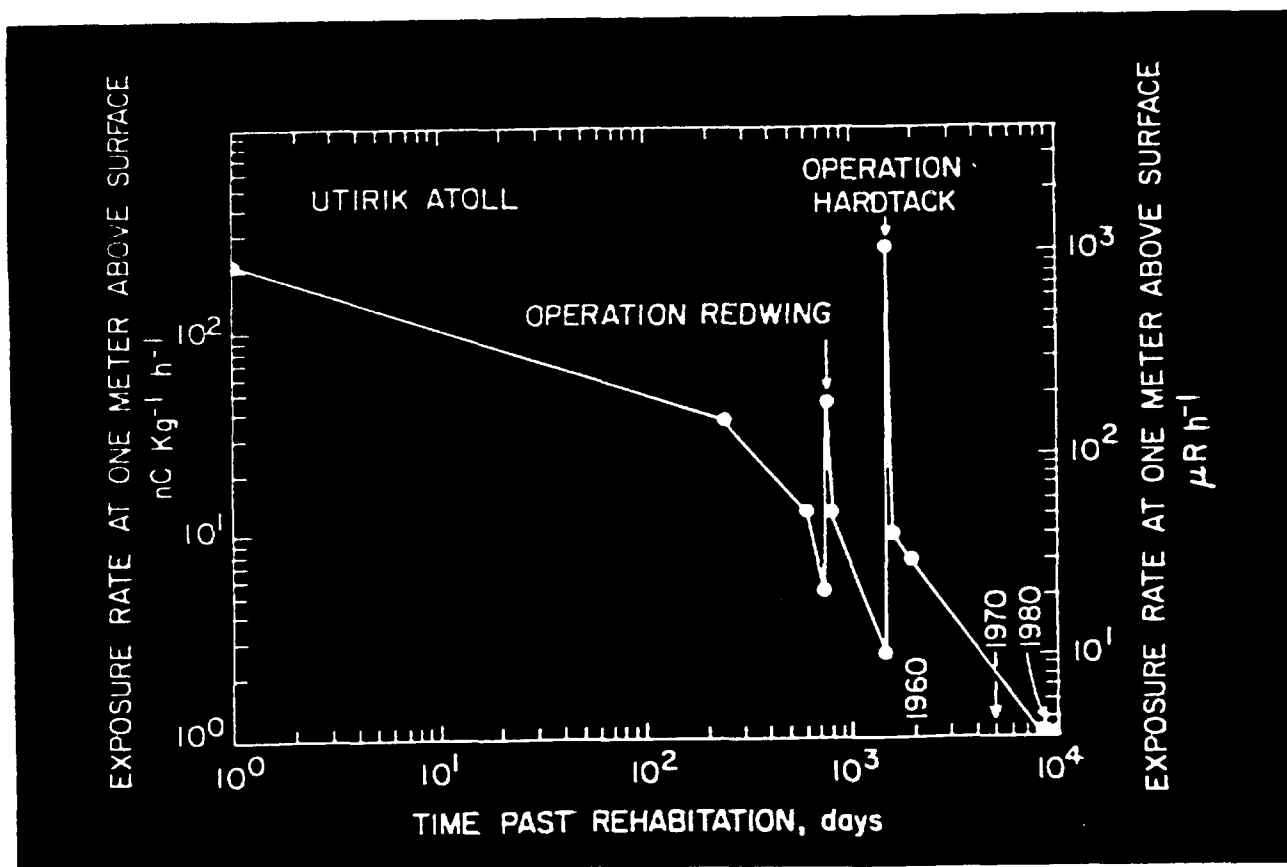
The equipment used were a Reuter Stokes environmental radiation monitor, model RSS-111, and a Baird-Atomic scintillation detector consisting of a sodium iodide detector (2.5 cm in diameter by 3.9 cm in length) connected to a ratemeter readout. Portable survey meters were used to help locate gross changes in the external exposure rate. Lithium fluoride thermoluminescent dosimeters were left on Bikini Island for several months and retrieved in December 1975.

Environmental exposure levels were assessed via the RSS-111. The NaI gamma spectrometer was used by us to determine the photon energy distribution and to compensate for the nonlinearity in the RSS-111 instrument response.



SLIDE 43

Environmental levels of external exposure. Exposure rates were observed to decline following each test. At Rongelap and Utirik the residual radiation from BRAVO fallout overshadowed the residual radiation from other tests. Occasional elevations due to fresh fallout were evident, however, the exposure rate would return to the BRAVO baseline within several weeks. The levels at Bikini Island during the early 70's were about 5 times the levels at Rongelap. The levels on the southern islands of Enewetak are very close to natural background;  $10^{-9}$  C kg<sup>-1</sup> h<sup>-1</sup> (3.7  $\mu$ R h<sup>-1</sup>). This low-level was due to the extensive clean-up at Enewetak prior to rehabilitation.



SLIDES 45-47

Mode of intake. Ingestion of fish and locally grown food items were assumed to be predominant intake pathways. This hypothesis was based on direct observation of diet habits, the correspondance of increasing or decreasing body burdens with availability of locally grown food products, and the results of airborne activity measurements.

The dietary intake of  $^{137}\text{Cs}$  was a major component contributing to the committed effective dose equivalent for the years after the initial contamination of the atolls. For persons whose diet included fish,  $^{65}\text{Zn}$  was a major component of committed effective dose equivalent for the initial years post return to Utirik.

Diet habits varied from atoll to atoll and depended on the quantity and quality of imported foods. At Bikini during the 1970's and when body burdens rose rapidly, imported foods were described as bland and tasteless. Differences in diet were observed directly by us and may be related to the fact that atoll to atoll body-burden ratios were not similar to ratios for levels of activity in plants or animals.









SLIDES 48-50

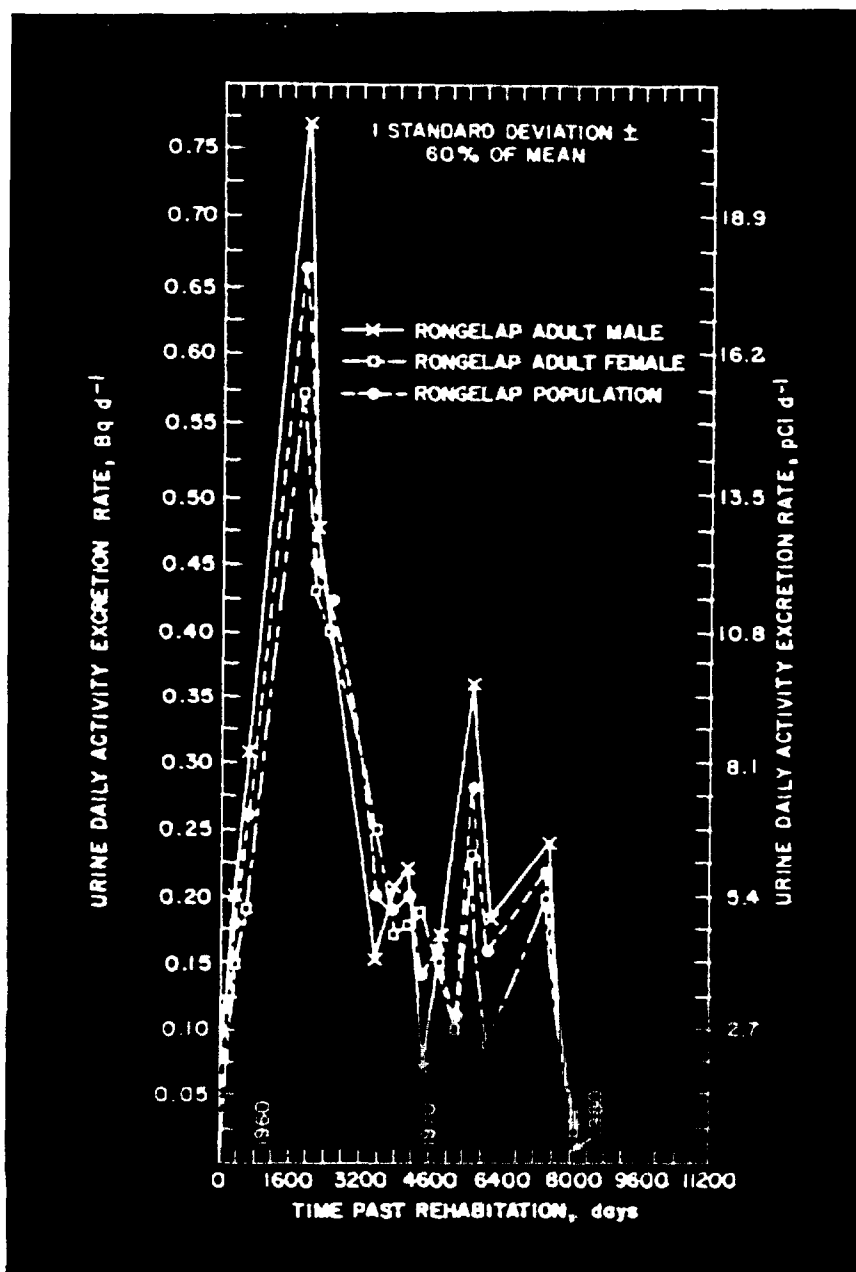
Impact of living pattern on external whole-body dose. The external radiation exposure rate data were measured by many individuals and an explanation of their methods can be found in their reports (Ch60, He65, Gr77b, JCAE57, T181, USPHS59). A factor of  $2.8 \times 10^{-8}$  Gy in tissue of interest per nC kg<sup>-1</sup> (0.73 rad/R) measured in air at 1 m above the surface was used by us to convert their data to absorbed dose in tissue. This factor was based on several considerations. First, the planar source represented by the flat atoll was assumed by us to be an exponential distribution of <sup>137</sup>Cs activity with depth in soil, typical of aged fallout (Be70). The nature of this source caused minimal variation of absorbed dose with depth or organ; however, the difference in number of electrons per gram of air and per gram of tissue necessitated a correction. Secondly, since the atolls presented a varying exposure rate environment, absorbed dose was adjusted for living pattern variations. Both of these considerations were combined by us to give the above factor used to convert external exposure to absorbed dose in tissue. Specific details on the adjustment for living pattern variation were given by Miltenberger and Greenhouse (Gr77b).



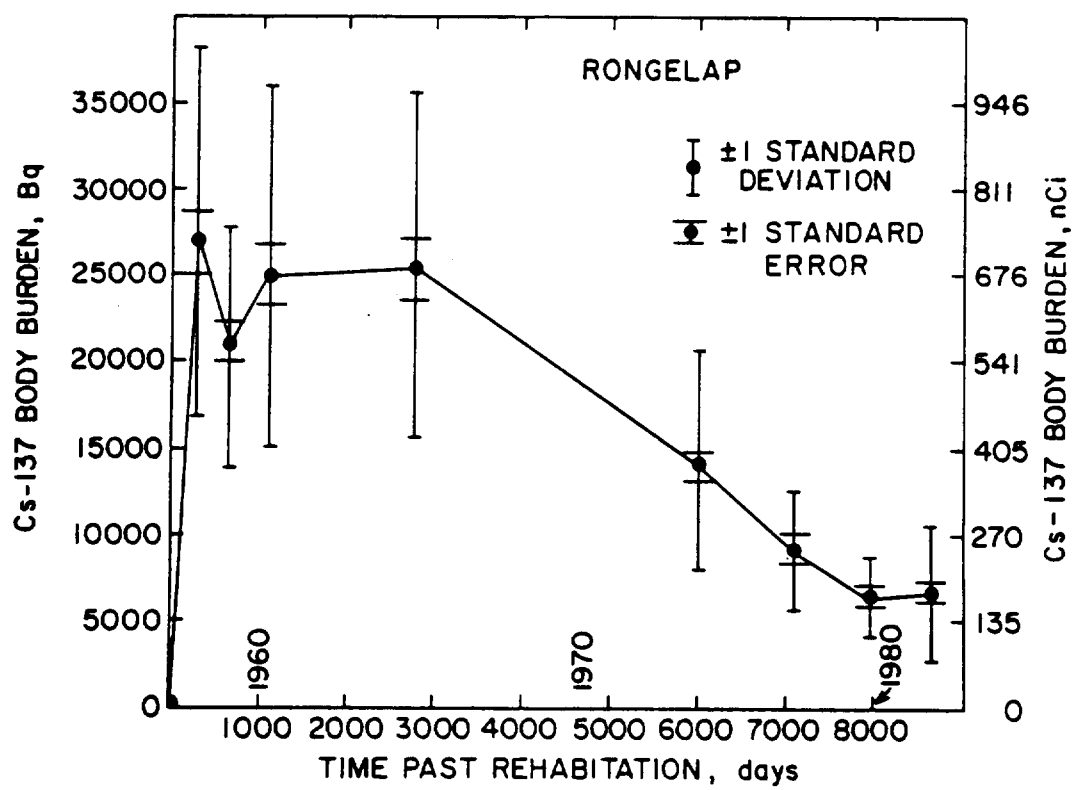


SLIDE 51 and 52

Body burden and excreta measurements. The body burdens which were measured directly had a standard deviation of  $\pm 30\%$  of the mean value for adults. The maximum body burden of  $^{137}\text{Cs}$  was observed to be 3 times the mean value. Indirect measure of body burden by urine analyses resulted in greater variation. The standard deviation for  $^{90}\text{Sr}$  was  $\pm 60\%$  of the mean value for adults. The standard error for the adult mean body burden was 5 times less than the standard deviation because many adults participated during each mission.





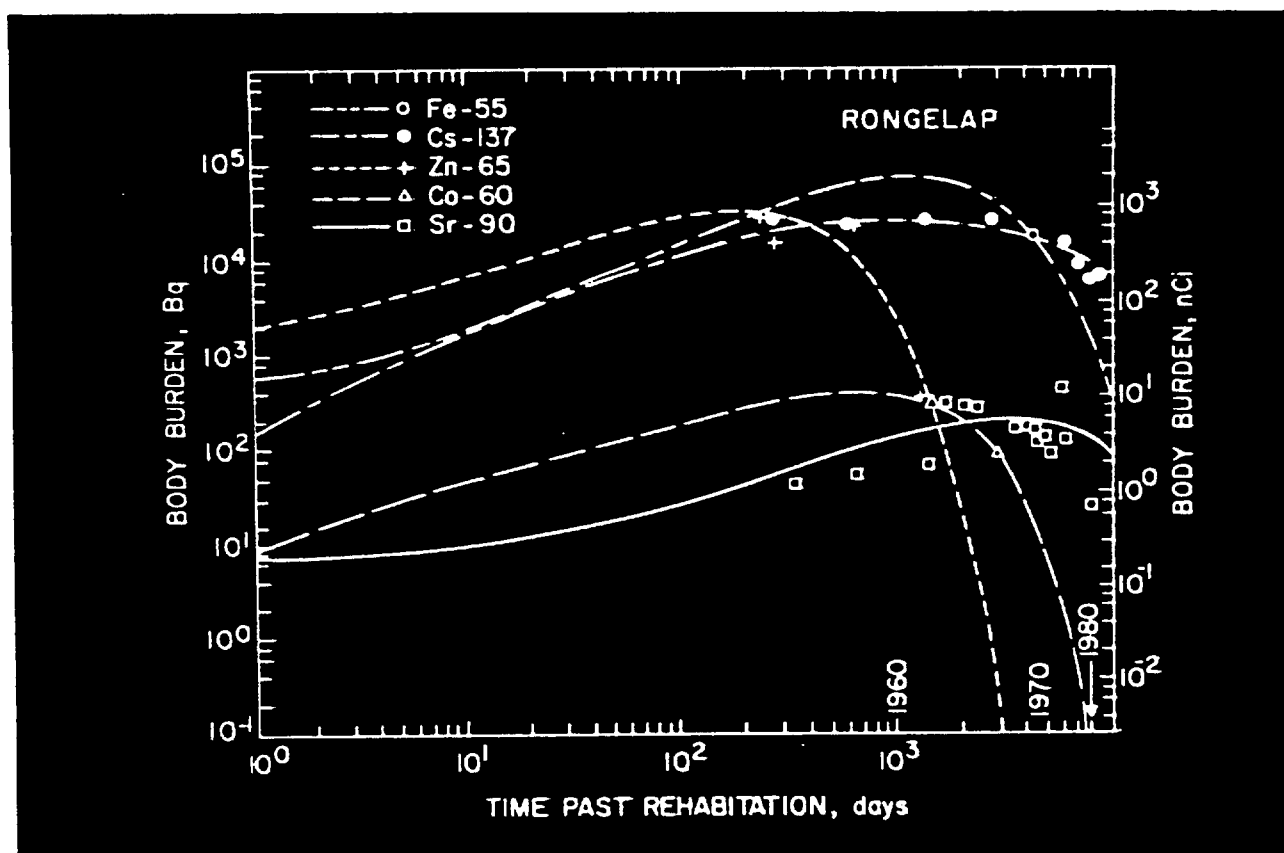


# SLIDE 53

Body burden history at Rongelap and Utirik. Adult average body-burden data and urine-activity concentration data were used as input quantities to equations which related them to activity intake rates. These input data were obtained from Conard's medical report (Co56, Co58, Co59, Co60, Co62, Co63, Co67, Co70, Co75, Wo59) and from recent surveys performed by members of the BNL Safety and Environmental Protection Division.

An equation was developed to relate the activity in the urine or whole body to the activity taken in by ingestion of contaminated food and fluids. To select an appropriate model for this relationship, we examined the body-burden history and the history of activity in vegetation and soil. Activity concentrations of  $^{137}\text{Cs}$ ,  $^{129}\text{I}$  and  $^{90}\text{Sr}$  in surface soil on Rongelap and Utirik Atolls were observed by us to decline with time at a rate greater than radioactive decay from 1954 to the present (Ne77, Ne79, Br82). Activity concentrations of  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  in vegetation were observed to decline at a rate greater than that predicted by radioactive decay alone (Ne77, Ne79). Body burdens and urine activity concentrations were observed to increase rapidly and to decline slowly throughout the residence time of persons at Rongelap and Utirik Atolls (Co75, Le80b). These observations led to the selection of a declining continuous intake model.

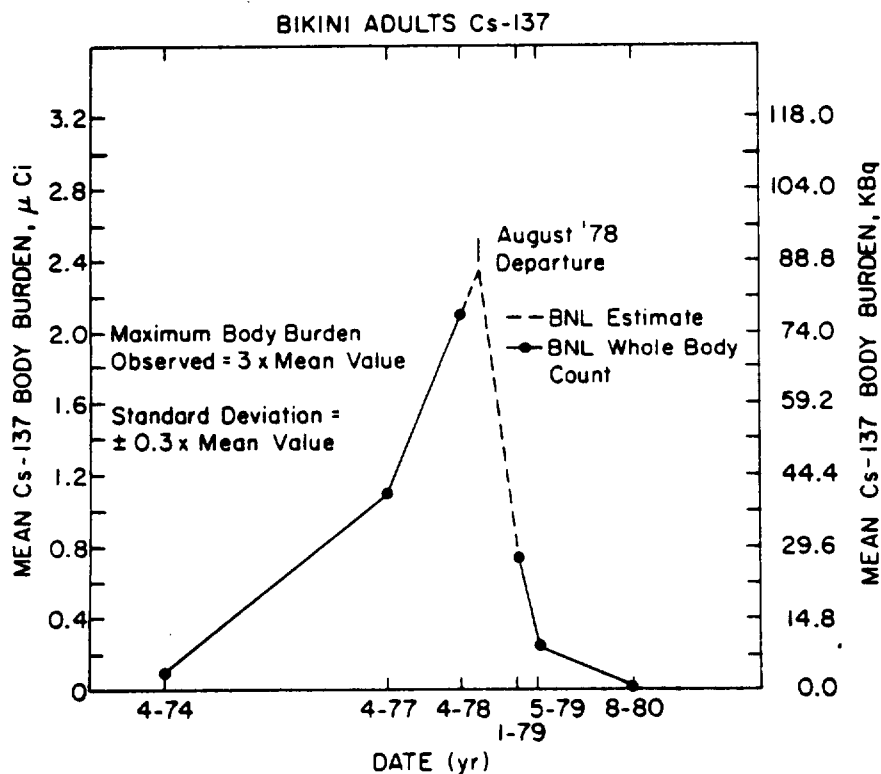
The lines fitting the declining continuous intake model at Rongelap are presented here. Measured results are plotted. The body burdens at Utirik were a factor of 2.6 times less than those at Rongelap for the period 1958 to 1984.



# SLIDE 54

Body-burden history at Bikini. Three body burden measurements of the Bikini Island population were conducted from 1974 to 1978 at Bikini Island. During this time, the mean  $^{137}\text{Cs}$  body burden of the adult Bikini population increased by a factor of 20. This dramatic elevation of body burden appears to be solely attributable to increased availability of locally grown food products, specifically coconuts and coconut plant products.

An ingestion intake model for stepwise increasing intake was used to estimate total  $^{137}\text{Cs}$  radioactivity ingested at Bikini. A constant continuous intake model was used by us to estimate total  $^{90}\text{Sr}$  intake.



## SLIDE 55

Status of plutonium measurements. The validity of the  $^{239}\text{Pu}$  data used to estimate the body burden at Rongelap Atoll in 1973 had been considered by an Energy Research and Development Agency ad hoc committee. The committee concluded that because of the possibility of urine-sample contamination these data were uncertain. This indeed may have been a factor since a radiochemical analysis of BRAVO debris indicated Rongelap Atoll was contaminated with  $^{239}\text{Pu}$  (Ts55). No special precautions had been taken when the urine samples were collected in the field, therefore not much credence could be given to these results.

In 1976, three male adults at Rongelap Atoll provided urine samples for  $^{239}\text{Pu}$  analysis. Two yielded results below the minimum detection limit of  $3.7 \times 10^{-4} \text{ Bq l}^{-1}$  ( $10 \text{ fCi l}^{-1}$ ) and one yielded  $3.3 \times 10^{-3} \text{ Bq l}^{-1}$  ( $90 \text{ fCi l}^{-1}$ ). The average of these values along with the 1973 adult average result that was reported by Conard (Co75) were used to derive potential body burdens.

The estimates for  $^{239}\text{Pu}$  adult body burden were not used to derive values of intake and committed effective dose equivalent since they may have been the result of an erroneous urine collection technique and not the result of internal deposition. The potential for contamination existed for  $^{90}\text{Sr}$ , however the impact of contamination on dose assessment was much greater for Pu.

Questions concerning the  $^{239}\text{Pu}$  estimates have led to study of the sampling and analysis procedures which indicated to us that some  $^{239}\text{Pu}$  in urine may not have been chemically recovered along with the tracer (Ry82). In August 1981, fecal and urine samples were obtained from Rongelap and Utirik residents and are to be analyzed after complete dissolution followed by a liquid solvent extraction technique. This method is being developed to be used in conjunction with a photon-electron rejecting liquid scintillation spectrometer developed by McDowell and duplicated by us for low-level alpha spectroscopy (Mc72). The question following additional analysis of urine collected in 1979 and 1980 from former Bikini Atoll residents. The urines were collected in a contamination free environment and indicate higher than expected levels of  $^{239}\text{Pu}$ . Further analysis using fission track-etch techniques will be done to confirm these results. Additionally, a comparison population has been chosen and samples collected from them. The await analysis.

---

 $^{239}\text{Pu}$  MEASUREMENTS
 

---

Date	Male Adult Population	$^{239}\text{Pu}$ Excretion Rate $\text{mBq d}^{-1}$
1974	Bikini Males	0.9
1975	Bikini Males	0.7
1976	Bikini Males	0.5
1976	Bikini Males	0.4
1979	Bikini Males	2
1973	Rongelap Males, Females	9
1976	Rongelap Males	2

---



## SLIDE 56

Intake estimates and dose equivalent. Adult average values for activity ingestion rate on day of return were calculated for all nuclides at Rongelap, Utirik, or Bikini. This information was used to estimate adult body-burden histories based on the assumption of declining continuous intake or increasing intake.

The declining continuous intake equation provided us with a smooth body-burden function for Rongelap and Utirik adults. The equation was a tool to provide retroactive body-burden estimates during the early years post-return to Utirik. Few direct measurements were made at this time.

Biological variation and errors in the collection and analysis of urine samples introduced larger errors in body-burden estimates than did direct whole-body counting. These variations result in indirect  $^{90}\text{Sr}$  measurements of body burden deviating widely from the hypothetical curve. In contrast the  $^{137}\text{Cs}$  results fit the curve closely.

The method use to fit the data was not chosen to minimize the weighted sum of squares of deviations of the body-burden estimates. Instead average values of initial intake rate were selected to represent all the body-burden data. For Rongelap, the  $^{137}\text{Cs}$  body burdens varied from the fitted intake function by a maximum factor of 1.7 and an average factor of 1.4; the  $^{90}\text{Sr}$  body burdens varied from the fitted intake function by a maximum factor of 3 and an average factor of 1.6. These factors reflect the quality of fit for directly measured body burdens and urine-derived body burdens in general.

The integral intake for 50 years and the committed effective dose equivalent were derived quantities which depended on knowledge of the fitted intake function for each population. The 50-yr interval chosen for internal intake represented the years 1957-2007 for Rongelap residents. For Utirik residents, the 50-yr interval represented the years 1954-2004. The committed effective dose equivalent was based on this cumulated intake. At Bikini the integral intake was for a 4.5 year period, 1974-1978.

For the nuclide  $^{137}\text{Cs}$ , an age dependent retention function was incorporated into the fitted intake function. In the estimate of adult committed effective dose equivalent a body mass of 60 kg was used based on 28 years of adult body mass measurements.

---

### INTAKE ESTIMATES

Declining Continuous Intake  
Increasing Intake

### COMMITTED EFFECTIVE DOSE EQUIVALENT

Retention vs Age  
Body Mass

## SLIDE 57

Declining continuous intake. The intake removal rate constant calculated for each nuclide in the Rongelap and Utirik adult populations is given here. In the cases of the Rongelap and Utirik people for who sequential body-burden data were available, the constant was found to have a positive value for  $^{137}\text{Cs}$ ,  $^{65}\text{Zn}$ ,  $^{60}\text{Co}$ ,  $^{239}\text{Pu}$  and  $^{90}\text{Sr}$ . The  $^{239}\text{Pu}$  data for urine of three adult males at Rongelap in 1973 and 1976 provided a single tentative estimate. The value of the constant was  $7.5 \times 10^{-5} \pm 9.1 \times 10^{-5} \text{ d}^{-1}$ . For  $^{55}\text{Fe}$ , only one bioassay estimate was published as a result of studies by the BNL medical program (Be72, Co75); thus an estimate was not possible. For the estimate of cumulated  $^{55}\text{Fe}$  intake, the constant was assumed equal to zero. Thus, for  $^{55}\text{Fe}$ , radioactive decay was assumed by us to be the only cause of reduced daily activity intake during the residence interval.

Where data were available for comparison, the values of the constant for  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  were found to be similar for both males and females as well as for residents of both Rongelap and Utirik. The yearly percent decrease in the atom ingestion rate was computed. A 9% reduction in dietary  $^{137}\text{Cs}$  was computed for each year at Rongelap and Utirik. For dietary  $^{90}\text{Sr}$ , an 8% reduction was estimated. The  $^{60}\text{Co}$  and  $^{65}\text{Zn}$  intakes were reduced rapidly during the first years post-return to Rongelap Atoll. An 80% per year reduction in dietary  $^{65}\text{Zn}$  and a 60% per year reduction in dietary  $^{60}\text{Co}$  were observed for adults. Also, for adult males at Rongelap, a tentative value of 3% per year reduction in dietary  $^{239}\text{Pu}$  was estimated from sparse data.

---

DECLINING CONTINUOUS  
INTAKE

---

Nuclide	Intake Removal Rate Constant
$^{60}\text{Co}$	$2.0 \times 10^{-3} \text{ d}^{-1}$
$^{137}\text{Cs}$	$2.0 \times 10^{-4} \text{ d}^{-1}$
$^{65}\text{Zn}$	$1.3 \times 10^{-3} \text{ d}^{-1}$
$^{90}\text{Sr}$	$1.7 \times 10^{-4} \text{ d}^{-1}$

---

SLIDE 58

Rongelap summary. The nuclide giving the greatest internal committed effective dose equivalent at Rongelap was  $^{137}\text{Cs}$ . Diet items containing  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$  were those which were locally grown. Land animals also contained  $^{137}\text{Cs}$  and  $^{90}\text{Sr}$ . Diet items containing  $^{65}\text{Zn}$ ,  $^{60}\text{Co}$  and  $^{55}\text{Fe}$  were those which were taken from the lagoon.

---

1957-2007 RONGELAP  
PROTRACTED EXPOSURE  
SUMMARY

---

Nuclide	Bq 50 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
$^{60}\text{Co}$	40,000	0.00034
$^{137}\text{Cs}$	1,500,000	0.022
$^{65}\text{Zn}$	310,000	0.0019
$^{90}\text{Sr}$	9,000	0.00053
$^{55}\text{Fe}$	2,400,000	0.00048
External	Natural Background Subtracted	0.017
Total	—	0.042

---

## SLIDE 59

Utirik summary. Use of the body-burden extrapolation equation leads us to the conclusion that  $^{65}\text{Zn}$  could have been the major contributor to the ingested activity during the first years post-rehabilitation of Utirik Atoll. This was supported to some extent by a Japanese report (JCCRRER56) which indicated to us a rise in the photon count rate at the surface of various types of tuna retrieved from the Marshall Islands' fishing grounds from March to August 1954 (100-10,000 cpm). Fish with count rates greater than 100 cpm at the surface were discarded by the fishermen. Radiochemical techniques indicated the prominence of  $^{65}\text{Zn}$  in the tuna's edible flesh.

For committed effective dose equivalent, the impact of nuclides with a short mean residence time in the diet ( $^{65}\text{Zn}$ ,  $^{60}\text{Co}$ ) was greater at Utirik because the population reinhabited within months of the BRAVO event. The impact of nuclides with a long mean residence time in the diet ( $^{137}\text{Cs}$ ,  $^{90}\text{Sr}$ ,  $^{55}\text{Fe}$ ) was greater at Rongelap because of greater initial contamination.

---

1954-2004 UTIRIK  
PROTRACTED EXPOSURE  
SUMMARY

---

Nuclide	Bq 50 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
$^{60}\text{Co}$	54,000	0.00044
$^{137}\text{Cs}$	860,000	0.013
$^{65}\text{Zn}$	5,200,000	0.030
$^{90}\text{Sr}$	1,700	0.00010
$^{55}\text{Fe}$	1,900,000	0.00036
External	Natural Background Subtracted	0.041
Total	—	0.085

---

## SLIDE 60

Bikini summary. The nuclide  $^{65}\text{Zn}$  was not included in the dose equivalent at Bikini because it was not present at the onset of exposure. Blood bioassay was not done on Bikinians and no estimate of  $^{55}\text{Fe}$  dose equivalent was made by us. The predominant nuclide  $^{137}\text{Cs}$  was taken into the body at an ever increasing rate during the exposure interval and direct comparison with declining continuous intake at Rongelap or Utirik may be inappropriate. It is clear that  $^{137}\text{Cs}$ , dose equivalent relative to external dose equivalent was greater at Bikini than at the other atolls.

---

1974-1978 BIKINI  
PROTRACTED EXPOSURE  
SUMMARY

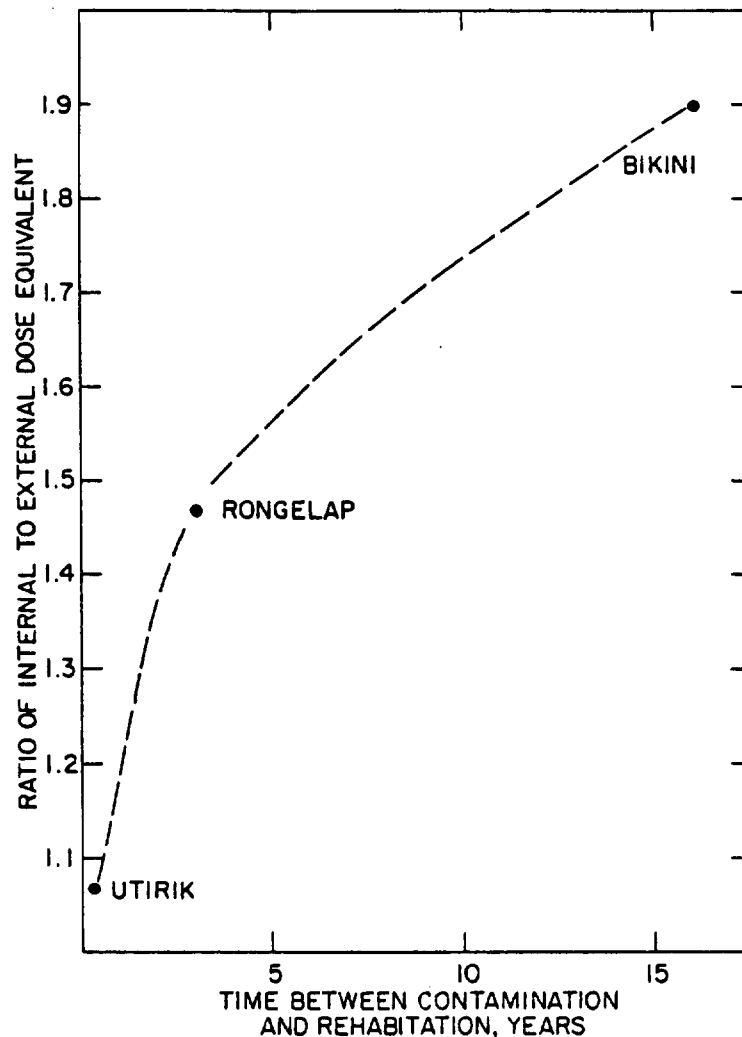
---

Nuclide	Bq 4.5 Year Intake	Sv Adult Mean Committed Effective Dose Equivalent
$^{60}\text{Co}$	3,900	0.000032
$^{137}\text{Cs}$	530,000	0.0084
$^{90}\text{Sr}$	4,200	0.0020
External	Natural Background Subtracted	0.0055
Total	—	0.016

---

SLIDE 61

Return to Bikini. The ratio of total internal committed effective dose equivalent to external dose equivalent was plotted by us versus time of return relative to the BRAVO detonation. It is apparent to us that the ratio increases with increasing time post return. In general, the ratio at Bikini Island would be about 2.5 if return in 2020 is hypothesized. From 2020 to 2050, we estimate an external whole body dose equivalent of 0.015 Sv (1.5 rem). The total estimate of internal plus external dose equivalent would be about 0.05 Sv (5 rem) for this 30 year period. Therefore, an unrestricted rehabilitation of Bikini Atoll might begin in 2020 if their environment is not cleaned-up. This dose equivalent estimate is exclusive of  $^{239}\text{Pu}$  dose equivalent.



## REFERENCES

- Ba10 Bateman, H., 1910, "The Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations", Proceedings of the Cambridge Philosophical Society, 15, 423.
- Be67 Berman, M., 1967, "The Iodine Pool", in: Compartments Pools and Spaces in Medical Physiology, U.S. Atomic Energy Commission Report, Symposium Series II, Washington, D.C.
- Be69 Bevington, P.R., 1969, "Data Reduction and Error Analysis for the Physical Sciences, New York", NY: McGraw-Hill Book Co.
- Be70 Bennett, B.G., 1979, "Estimation of Gonadal Absorbed Dose Due to Environmental Gamma Radiation", Health Physics, 19, 757-767.
- Be72 Beasley, T.M., Held, E.E. and Conard, R.A., 1972, "Iron-55 in Rongelap People, Fish and Soils", Health Physics, 22, 245-250.
- Be80 Beck, H. L., 1980, Exposure Rate Conversion Factors for Radionuclides Deposited on the Ground, Environmental Measurements Laboratory Report, New York, N.Y., EML-378.
- Bo56 Borg, D.C., 1956, "Theoretical Calculations of the Gamma Radiation Spectrum from Initial and Fallout Radiations of Nuclear Weapons", in: The Shorter-Term Biological Hazards of a Fallout Field, U.S. Atomic Energy Commission Report, Washington, D.C.
- Br74 Brauer, F.P. Soldat, J.D., Tenny, H., Strebin, R.S., "Natural Iodine and Iodine-129 in Mammalian Thyroids and Environmental Samples Taken From Locations in the United States", in: Environmental Surveillance Around Nuclear Installations II, International Atomic Energy Agency Report, IAEA-SM-180/34, Vienna

- Br80 Brauer, F.P. and Naidu, J., 1980, I-129 Analysis of Marshall Islands Environmental Samples, Analytical and Quality Assurance Procedures, Progress Report, Brookhaven National Laboratory, Upton, NY.
- Br82 Brauer, F.P. and Naidu, J.N., 1982, "I-129 Analysis of Marshall Islands Environmental Samples, Analytical and Quality Assurance Procedures", Battelle, Pacific Northwest Laboratories, Richland, WA, and Brookhaven National Laboratory, Upton, NY (unpublished manuscript).
- CBEIR80 Committee on the Biological Effects of Ionizing Radiation, 1980, The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980, National Research Council Report, National Academy Press, Washington, D.C.
- Ch60 Chakravarti, D. and Held, E.E., 1960, "Potassium and Cesium-137 in Birgus Latro (Coconut Crab) Muscle Collected at Rongelap Atoll", University of Washington Fisheries Laboratory Report, Seattle, WA, UWFL-64.
- Co55 Cohn, S.H., Rinehart, R.W., Gong, J.K., Robertson, J.S., Milne, W.L. and Bond, V.P., 1955, "Nature and Extent of the Internal Radioactive Contamination of Human Beings and Animals Exposed to Fallout Material in Operation Castle", U.S. Naval Radiological Defense Laboratory Report, San Francisco, CA, USNRDL-TR-86.
- Co56 Conard, R.A., Cannon, B., Huggins, C.E., Richards, J.B. and Lowery, A., 1956, "Medical Survey of Marshallese Two Years After Exposure to Fallout Radiation", Brookhaven National Laboratory, Upton, NY, BNL 412.



- Co58 Conard, R.A., Meyer, L.M., Rall, J.E., Lowery, A., Suen, A.B., Cannon, B., Carter, E.L., Eicher, M. and Hechter, H., 1981, "March 1957 Medical Survey of Rongelap and Utirik People Three Years After Exposure to Radioactive Fallout", Brookhaven National Laboratory, Upton, NY, BNL 501.
- Co59 Conard, R.A., et al., 1959, "Medical Survey of Rongelap People, March 1958, Four Years After Exposure to Fallout", Brookhaven National Laboratory, Upton, NY, BNL 534.
- Co60 Conard, R.A., et al., 1960, "Medical Survey of Rongelap People Five and Six Years After Exposure to Fallout (With an Addendum on Vegetation)", Brookhaven National Laboratory, Upton, NY, BNL 609.
- Co62 Conard, R.A., et al., 1962, "Medical Survey of Rongelap People Seven Years After Exposure to Fallout", Brookhaven National Laboratory, Upton, NY, BNL 727.
- Co63 Conard, R.A., et al., 1963, "Medical Survey of Rongelap People Eight Years After Exposure to Fallout", Brookhaven National Laboratory, Upton, NY, BNL 780.
- Co65 Conard, R.A., et al., 1965, "Medical Survey of the People of Rongelap and Utirik Islands Nine and Ten Years After Exposure to Fallout Radiation (March 1963 and March 1964)", Brookhaven National Laboratory, Upton, NY, BNL 908.
- Co67 Conard, R.A., et al., 1967, "Medical Survey of the People of Rongelap and Utirik Islands Eleven and Twelve Years After Exposure to Fallout Radiation (March 1965 and March 1966)", Brookhaven National Laboratory, Upton, NY, BNL 50029.

- Co70 Conard, R.A., et al., 1970, "Medical Survey of the People of Rongelap and Utirik Islands Thirteen, Fourteen and Fifteen Years After Exposure to Fallout Radiation (March 1967, March 1968, and March 1969)", Brookhaven National Laboratory, NY, BNL 50220.
- Co72 Cole, R., 1972, Inhalation of Radioiodine from Fallout: Hazards and Countermeasures, Environmental Science Associates Report, Burlingame, CA, ESA-TR-72-01.
- Co75 Conard, R.A., et al., 1975, "A Twenty-Year Review of Medical Findings in a Marshallese Population Accidentally Exposed to Radioactive Fallout", Brookhaven National Laboratory, Upton, NY, BNL 50424.
- Co77 Personal Communications with S. Cohn, Medical Department, Brookhaven National Laboratory, Upton, NY.
- Co80a Conard, R.A., et al., 1980, "Review of Medical Findings in a Marshallese Population Twenty-Six Years After Accidental Exposure to Radioactive Fallout", Brookhaven National Laboratory, Upton, NY, BNL 51261.
- Co80b Conard, R.A., 1980, Private Communication, Brookhaven National Laboratory, Upton, NY, 11973.
- Coh60 Cohn, S.H., Robertson, J.S. and Conard, R.A., 1960, "Radioisotopes and Environmental Circumstances: Internal Radioactive Contamination of a Pacific Island Community Exposed to Local Fallout", in: Radioisotopes in the Biosphere (Minneapolis, MN: University of Minnesota Press).
- Coh63 Cohn, S.H., Conard, R.A., Gusmano, E.A. and Robertson, J.S., 1963, "Use of a Portable Whole Body Counter to Measure Internal Contamination in a Fallout Exposed Population", Health Physics, 9, 15-23.

- Coh56 Cohn, S.H., Rinehart, R.W., Gong, J.K., Robertson, J.S., Milne, W.L., Bond, V.P. and Cronkite, E.P., 1956, "Internal Deposition of Radionuclides in Human Beings and Animals", in: Some Effects of Ionizing Radiation on Human Beings, U.S. Atomic Energy Commission, Washington, DC, USAEC-TID 5358.
- Cr56 Cronkite, E.P., Bond, V.P. and Dunham, C.L., 1956, "A Report on the Marshallese and Americans Accidentally Exposed to Radiation from Fallout and a Discussion of Radiation Injury in the Human Being", in: Some Effects of Ionizing Radiation on Human Beings, U.S. Atomic Energy Commission, Washington, DC, USAEC-TID 5358.
- Cr63 Crocker, G.R., 1963, Estimates of Fission Product Yields of a Thermo-nuclear Explosion, United States Naval Radiological Defense Laboratory Report, San Francisco, CA, USNRDL-TR-642.
- Cr65 Crocker, G. R. and Turner, T., 1965, Calculated Activities, Exposure Rates, and Gamma Spectra for Unfractionated Fission Products, United States Naval Radiological Defense Laboratory Report, San Francisco, CA, USNRDL-TR-1009.
- De75 De Groot, L.J., 1975, "Thyroid Carcinoma", Med. Clin. N.A., 59, 1233.
- Du56 Dunning, G.M. and Hilcken, J.A. (eds.), 1956, "The Shorter-Term Biological Hazards of a Fallout Field", Symposium, 12-14 December (Washington, DC: U.S. Atomic Energy Commission and Department of Defense).
- Du57 Dunning, G.M., 1957, "Radioactive Contamination of Certain Areas in the Pacific Ocean from Nuclear Tests", United States Atomic Energy Commission, Washington, DC.

- Ev66 Eve, I. S., 1966, "A Review of the Physiology of the Gastrointestinal Tract in Relation to Radiation Doses from Radioactive Materials", Health Physics, 12, 131-161.
- Fr61 Freiling, E. C., 1961, "Radionuclide Fractionation in Bomb Debris", Science, 133, 1991-1998.
- G162 Glasstone, S. (ed.), 1962, "The Effects of Nuclear Weapons, Defense Atomic Support Agency", Department of Defense (Washington, DC: U.S. Atomic Energy Commission).
- Gr77a Greenhouse, N.A., Miltenberger, R.P and Cua, F.T., 1977, "Radiological Analyses of Marshall Islands Samples 1974-1976", Brookhaven National Laboratory, Upton, NY, BNL 50796.
- Gr77b Greenhouse, N.A. and Miltenberger, R.M., 1977, "External Radiation Survey and Dose Predictions for Rongelap, Utirik, Rongerik, Ailuk, and Wotje Atolls", Brookhaven National Laboratory, NY, BNL 50797.
- Gr79 Greenhouse, N.A., Miltenberger, R.P. and Lessard, E.T., 1979, "External Exposure Measurements at Bikini Atoll", Brookhaven National Laboratory, Rep. BNL 51003.
- Gu76 Gudiksen, P.H., Crites, T.R. and Robison, W.L., 1976, "External Dose Estimates for Future Bikini Atoll Inhabitants", Lawrence Livermore Laboratory, Rep. UCRL-51879, Rev. 1.
- Ha54 Harris, P.S., 1954, A Summary of the Results of Urine Analyses on Rongelap Natives, Americans and Japanese Fisherman to Date, Los Alamos Scientific Laboratory, Internal Memorandum, Los Alamos, NM.
- Ha63 Harrison, J., 1963, "The Fate of Radioiodine Applied to Human Skin", Health Physics, 9, 993-1000.

- Ha79 Hawthorne, H.A., Editor, 1979, Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251, Defense Nuclear Agency Report, DNA 1251-2-Ex, Santa Barbara, CA.
- He65 Held, E., 1965, "Gamma Dose at Rongelap Atoll, 1954-1963", Laboratory of Radiation Biology, University of Washington, Seattle, WA, UWFL0-91.
- Hi81 Hicks, H.G., 1981, Results of Calculations of External Gamma- Radiation Exposure Rates from Fallout and the Related Radionuclide Compositions, Lawrence Livermore National Laboratory Report, Livermore, CA, UCRL-53152.
- Ho63 Holland, J. Z., 1963, "Distribution and Physical-Chemical Nature of Fallout", Federation Proceedings, 22, 1390-1397.
- ICRP59 International Commission on Radiological Protection, 1959, Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2 (London: Pergamon Press).
- ICRP68 International Commission on Radiological Protection, 1968, Report of Committee IV on Evaluation of Radiation Doses to Body Tissues from Internal Contamination Due to Occupational Exposure, ICRP Publication 10 (London: Pergamon Press).
- ICRP69 International Commission on Radiobiological Protection, 1969, Report of Committee IV on the Assessment of Internal Contamination Resulting from Recurrent or Prolonged Uptakes, ICRP Publication 10A (London: Pergamon Press).
- ICRP72 International Commission on Radiological Protection, 1972, Alkaline Earth Metabolism in Adult Man, ICRP Publication 20, Pergamon Press, Oxford.

- ICRP74 International Commission on Radiological Protection, 1974, Report of the Task Group on Reference Man, ICRP Publication 23 (London: Pergamon Press).
- ICRP79 International Commission on Radiological Protection, 1979, Report of Committee II on Limits for Intakes of Radionuclides by Workers, ICRP Publication 30 (Oxford: Pergamon Press).
- Is56 Ishibasi, M., Shigematsu, T., Ishida, T., Okada, S., Nishi, T., Takahashi, H., Matsumoto, C., Shimizu, S., Hyodo, T., Hirayama, F. and Okamoto, S., 1956, "Radiochemical Analysis of the Bikini Ashes", in: Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science, Tokyo.
- Ja64 James, R.A., 1964, Estimate of Radiation Dose to Thyroids of Rongelap Children Following the BRAVO Event, Lawrence Radiation Laboratory Report, Livermore, CA, UCRL-12273.
- JCAE57 Joint Committee On Atomic Energy, 1957, The Nature of Radioactive Fall-Out and Its Effects on Man, Part 1, Washington, DC.
- JCCRRER56 Japan Committee for Compilation of Reports on Research in the Effects of Radioactivity, 1956, Research in the Effects and Influences of the Nuclear Bomb Test Explosions, (Tokyo: Japan Society for Promotion of Science).
- Jo81 Johnson, J.R., 1981, "Radioiodine Dosimetry", Journal of Radioanalytical Chemistry, 65, 223-238.
- Jo82 Johnson, J.R., 1982, "Fetal Thyroid Dose From Intakes of Radioiodine by the Mother", Health Physics, 43, 573-582.

- Ka66 Kawahara, F. K., O'Conner, J. D., Lee, H. and Connors, M. A., 1966, Local Fallout From Nuclear Test Detonations, Vol. III, Defense Atomic Support Agency, San Francisco, CA, DASA 1251.
- Ke65 Keisch, B., Koch, R.C., Levine, A.L., 1965, "Determination of Biospheric Levels of I-129 by Neutron-Activation Analysis", in: Modern Trends in Activation Analysis, Texas A&M University Report, College Station, TX.
- Ki56 Kimura, K., 1956, "Radiochemical Studies on the Radioactive Dust Due to the Nuclear Detonation at the Bikini Atoll on 1st March, 1954", in: Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science, Tokyo.
- Ki78 Killough, G.G., Dunning, D.E., Bernard, S.R. and Pleasant, J.C., 1978, "Estimates of Internal Dose Equivalent to 22 Target Organs for Radionuclides Occurring in Routine Releases from Nuclear Fuel-Cycle Facilities", Oak Ridge National Laboratory, Oak Ridge, TN, NUREG/CR-0150, ORNL/NUREG/TM190.
- Ko80 Kocher, D., C., 1980, "Dose Rate Conversion Factors for External Exposure to Photon and Electron Radiation from Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities", Health Physics, 38, 543-621.
- La65 Lavrenchik, V. N., 1965, Global Fallout Products of Nuclear Explosions, Atomic Energy Commission Report, Washington, D.C., AEC-tr-6666.
- Le78 Lederer, C. M., and Shirley, V. S., Editors, 1978, Table of The Isotopes, Seventh Edition, John Wiley and Sons, Inc., New York, NY.

- Le80a Lessard, E.T., Miltenberger, R.P. and Greenhouse, N.A., 1980, "Dietary Radioactivity Intake from Bioassay Data: A Model Applied to <sup>137</sup>Cs Intake by Bikini Island Residents", Health Physics, 39, 177-183.
- Le80b Lessard, E.T., Greenhouse, N.A. and Miltenberger, R.P., 1980, "A Reconstruction of Chronic Dose Equivalents for Rongelap and Utirik Residents - 1954 to 1980", Brookhaven National Laboratory, Upton, NY, BNL 51257.
- Le80c Lessard, E.T. and Miltenberger, R.P., October 1980, "July-August 1980 Field Trip Report to Thomas McCraw", U.S. Department of Energy, Brookhaven National Laboratory, Upton, NY, 11973.
- Le84 Lessard, E. T., Miltenberger, R. P., Cohn, S. H., Musolino, S. V. and Conard, R. A., 1984, "Protracted Exposure to Fallout, the Rongelap and Utirik Experience" Health Physics, 46, 511-527.
- Ma56 Mather, R.L., 1956, "Brief Summary of Gamma Radiation Spectra from Residual Radiation Sources Following a Nuclear Detonation", in: The Shorter-Term Biological Hazards of a Fallout Field, United States Atomic Energy Commission and Department of Defense Report, Washington, D.C.
- Ma81 Mattson, Sorén, et al., 1981, "Excretion of Radionuclides In Human Breast Milk Following Administration of I-125 Fibrinogen, Tc-99-MAA and Cr-51 EDTA", in: Third International Radiopharmaceutical Dosimetry Symposium, Conference Proceedings, Oak Ridge, TN, FDA 81-8166.



- Mc72 McDowell, W.J. and Henley, L.C., 1972, "An Evaluation of the Possibility of Detecting and Identifying Alpha Emitters in Low-Count Rate Samples", Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-3676.
- Mi80 Miltenberger, R.P., Greenhouse, N.A. and Lessard, E.T., 1980, "Whole Body Counting Results from 1974 to 1979 for Bikini Islands Residents", Health Physics, 39, 395-407.
- Mi81 Miltenberger, R.P., Lessard, E.T. and Greenhouse, N.A., 1981, "<sup>60</sup>Co and <sup>137</sup>Cs Long-Term Biological Removal Rate Constants for the Marshallese Population", Health Physics, 40, 615-623.
- Mi83 Miltenberger, R. P. and Lessard, E. T., Editors, 1983, Body Burdens and Dose Assessment for Bikini Island Residents, Brookhaven National Laboratory Report, Upton, NY, BNL Draft.
- Na80 Naidu, J.R., Greenhouse, N.A., Knight, G. and Craighead, E.C., 1980, "Marshall Islands: A Study of Diet and Living Patterns", Brookhaven National Laboratory, Upton, NY, BNL 51313.
- Ne77 Nelson, U.A., 1977, "Radiological Survey of Plants, Animals and Soil at Christmas Islands and Seven Atolls in the Marshall Islands", Laboratory of Radiation Ecology, University of Washington, Seattle, WA, NUO-269-32.
- Ne79 Nelson, U.A., 1979, "Radiological Survey of Plants, Animals and Soil at Five Atolls in the Marshall Islands", Laboratory of Radiation Ecology, University of Washington, Seattle, WA, NUO-269-36.
- No66 Norment, H. G., Schwenke, T. W. and Kohlberg, I., 1966, Development of an Improved Land-Surface Fallout Model, Technical Operations Research Report, Burlington, MA, TO-B 65-99.

- NNDC82      National Nuclear Data Center, 1982, Evaluated Nuclear Data Files, Brookhaven National Laboratory Report, Upton, NY, ENDF BIV.
- OC68      O'Conner, J.D. and Crocker, G.R., 1968, Local Fallout From Nuclear Test Detonations, Defense Atomic Support Agency, Naval Radiological Defense Laboratory, San Fransisco, CA, DASA 1251.
- Ro77      Robison, W.L., Phillips, W.A. and Colsher, C.S., 1977, "Dose Assessment at Bikini Atoll", Lawrence Livermore Laboratory, Rep. UCRL-51879, Part 5.
- Ry82      Ryan, M.T., Case, G.N., McDowell, W.J. and Henley, L.C., 1982, "A Preliminary Comparison of Two Techniques for Bioassay of Urine for Plutonium", Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/Tm-8531.
- Sh57      Sharp, R., and Chapman, W., 1957, Exposure of Marshall Islanders and American Military Personnel to Fallout, Naval Medical Research Institute, Bethesda, MD, WT-938.
- Sk75      Skrabble, K., French, C., Chabot, G., Major, A. and Ward, K., 1974, "Kinetics Equation for Linear First-Order Nuclear Phenomena", Nuclear Safety, 16, 337-344.
- So55      Sondhaus, C.A., and Bond, V.P., 1955, Physical Factors and Dosimetry in the Marshall Islands Radiation Exposures, Naval Medical Research Institute Report, Bethesda, MD, WT-939.
- St62      Studier, M., Postmus, H.C., Jr., Mech, J., Walters, R.R., Sloth, E.N., 1962, "The Use of I-129 as an Isotopic Tracer and its Determination Along With Normal I-127 by Neutron Activation — The Isolation of Iodine from a Variety of Materials", Journal of Inorganic Nuclear Chemistry, 24, 755.

- Su56 Suito, E., Tokiyama, K. and Uyeda, N., 1956, "Colloid Morphological and Crystalline Studies of Bikini Dust", Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science, Tokyo.
- Ti81 Tipton, W.J. and Melbaum, R.A., 1981, "An Aerial Radiological and Photographic Survey of Eleven Atolls and Two Islands within the Northern Marshall Islands", DOE Remote Sensing Laboratory, Las Vegas, NV, E66-1183-1758.
- Ts55 Tsuzuki, M., 1955, "Erfahrungen uber Radioaktive Schädigung der japanische Fisher durch Bikini-asche", Muench. Med. Wochsch., 31, 988-994.
- USPHS59 United States Public Health Service, 1959, Report of the Public Health Service Off-Site Radiological Monitoring Data, Operation Hardtack Phase I 1958, publisher unknown, manuscript attached to letter from Lt. Colonel Belmont Evans, (USA) to Robert Conard, M.D., Brookhaven National Laboratory, Upton, NY.
- Wo59 Woodward, K., Schrodtt, A., Anderson, J., Claypool, H. and Hartgering, J., 1959, "The Determination of Internally Deposited Radioactive Isotopes in the Marshallese People by Excretion Analysis", Defense Atomic Support Agency, Walter Reed Army Institute of Research, Washington, DC, DASA 1180.
- Ya56 Yamatera, 1956, "Radiochemical Analysis of Dust Due To the Thermonuclear Test on March 1, 1954", in: Research in the Effects and Influences of the Nuclear Bomb Test Explosions, Japan Society for the Promotion of Science, Tokyo.

